

THE DUST HAZARD
IN INDUSTRY

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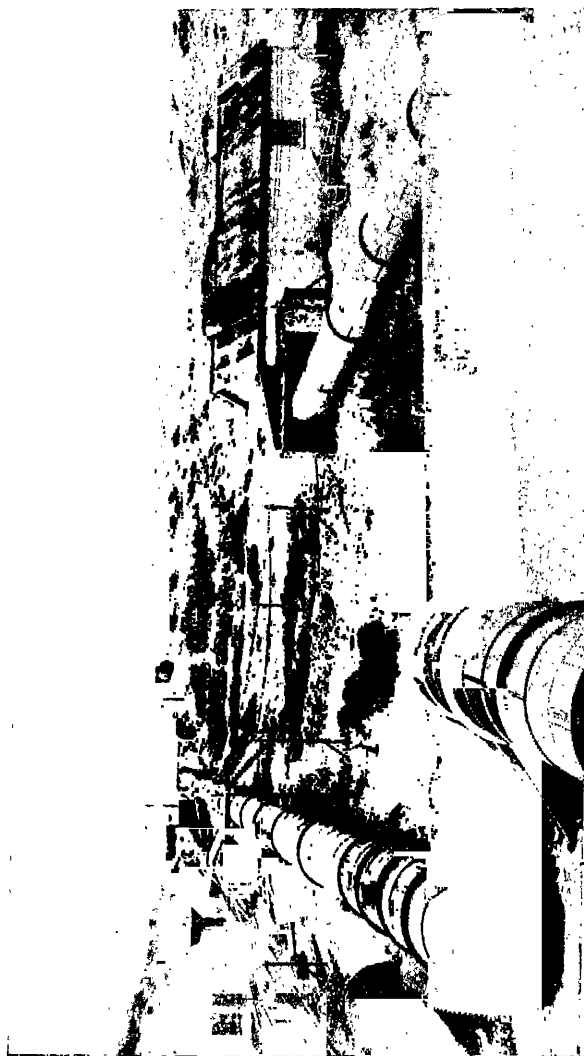
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[Frontispiece.]

THE DEPARTMENT OF MINES EXPERIMENTAL STATION, ESKMEALS.

THE DUST HAZARD IN INDUSTRY

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IN GASES, AND THEIR PRACTICAL APPLICATIONS"



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PREFACE

THE presence of dust, whether in industry or in daily life, is generally unwelcome. The dust that is produced in certain industrial operations is frequently a source of serious danger either to health, by inducing chronic diseases of the respiratory and other organs, or to life and property, by causing disastrous explosions. In writing this book, an attempt has been made to prepare a concise, yet comprehensive, summary of the available information relating to the characteristic properties and behaviour of matter in the form of dust, the various conditions that contribute to the hazardous character of certain dusty occupations, and the means that can be employed to minimise—or, where possible, to eliminate—the dust hazard.

A great deal of valuable information has been obtained, and placed at the disposal of those interested, by the Home Office in this country, and by Public Health departments abroad—particularly in the U.S.A., where valuable work has been undertaken by the Bureau of Mines, and the Bureau of Chemistry of the Department of Agriculture. A wide and varied literature of the subject is scattered through the technical and scientific Press.

• It is hoped that, in making such information readily accessible, this book will contribute something towards a wider knowledge of the various hazards that are due to dust. To be forewarned is to be forearmed, and, possibly, a wider dissemination of such information will enable those engaged in dusty occupations to guard against

the risks that are associated with the production of dust.

My grateful acknowledgements are due for permission to reproduce illustrations to :

Prof. R. V. Wheeler, for the frontispiece and Figs. 5, 6 and 7, that are taken from the reports of the Explosions in Mines Committee.

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I am grateful to Mr. C. Calder and Mr. H. W. Richards, B.Sc., for preparing drawings of illustrations, and to Miss Margaret Gray for compiling the index and preparing the typescript for the press.

W. E. G.

• *Runcorn,*
January 1925.

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THE DUST HAZARD IN INDUSTRY

CHAPTER I

INTRODUCTION

" . . . All our yesterdays have lighted fools
The way to dusty death."—MACBETH, v, 5, l. 22.

THE words of Macbeth's gloomy self-indictment might be applied with considerable force to our industrial system, with its smoky skies and dusty streets that substitute dirt and disease for sunshine and health, its occupational diseases with their tragically high death-rate, and its frequent fatal dust explosions in factories and mines.

All too often, dust has been looked upon as a necessary evil. The grime and smoke of a manufacturing town were regarded with pride as the unmistakable evidence of industrial prosperity. The workers in certain dusty occupations continually inhaled the dusty air, and slowly choked to death. The miller wore a white hat and, every now and then, his mill was blown sky-high.

Generally speaking, it is through ignorance or indifference that dust is allowed to become a nuisance and a danger. In the past, ignorance was general, and the workers suffered; to-day, however, ignorance is less excusable, and, in many cases, there need be neither dust nuisance nor dust hazard. A great deal of the dust and smoke nuisance that exists in our towns and industrial centres is due to the apathy of the general public and the resulting lack of an organised public opinion.

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The continued existence of a dust hazard is frequently due to a degree of indifference on the part of the responsible employer or workman that amounts to culpable negligence.

In this little book, we are not concerned with the dust and smoke *nuisance*; this aspect of the question merits separate treatment. Here we are concerned, first, with the danger to health that arises when certain dusts are inhaled or handled by the workers, and, secondly, with the danger to life and property that is associated with the explosion of a cloud of inflammable dust.

DUSTY AIR

It has been shown that the normal dust content of the atmosphere is less than 1 mgm. per cubic metre in country districts and over the sea, between 1 and 3 mgms. in a town, and as much as 5 mgms. in an industrial centre. Naturally, the amount is greater in dry weather.

The composition of the dust also varies according to the locality. Over the sea, the dust consists almost entirely of salt particles that are formed by the evaporation of spray. In a country district, pollen or soil particles will predominate, according to the season and the weather, while smoke particles from a distant manufacturing town or salt dust from the sea will be found, when the wind blows from those quarters. Street dust contains soot and flue dust, mineral dust from street paving and buildings, organic matter from garbage and decaying leaves, dust worn off boots and clothes, manure of horses, dung of dogs,

fragments of insects and their eggs, mould spores, plant pollen, bacteria.

In many industries, the normal dustiness of the air is greatly increased by dust that is produced in the course of the manufacturing operations. Generally, it is produced as a direct result of some disintegration process. Among the most dusty trades are the grinding and polishing of metals, the milling of starch, cereals and nuts, the crushing and grinding of rocks, minerals, and many inorganic and organic substances, the manufacture and working of textiles, the drilling and blasting of rocks in mines and quarries, the working of builder's stone, glass, leather, cork, graphite, etc. The atmosphere in which these operations are performed may contain up to 30 mgms., and, in some instances, as much as 400 mgms., of dust per cubic metre of air. In Table I are shown (*a*) the average quantities of dust in milligrams per cubic metre that are commonly present in the air in certain working environments, and (*b*) the average number of dust particles per cubic centimetre of the air.

In town air and in many badly ventilated workshops in which open fires are used, the majority of the particles are black smoke particles. These are found to be singularly uniform in size, ranging from 0.25 to 1 μ , and averaging about 0.5 μ .

The extremely fine character of the dust that is produced in such occupations as iron-grinding and gold-mining is reflected in the relatively high number of particles per cubic centimetre.

The apparent dustiness of the air in a factory or workroom depends very much upon the colour

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TABLE I (a).

Locality.	Mgms. dust per cubic metre air.	Remarks. ($1\mu = 0.001$ cm.).
Garden, Edgbaston, after 4 days' fine weather.	0.28	
Same, after 36 hours' heavy rain.	0.07	
Open air, Stoke (manu- facturing district).	0.94	
Centre of laboratory, Stoke.	1.85	
Polishing room (floor unswept).	5.4	
Same, with floor swept.	1.6	
Grinding table blades.	22.0	Small room, badly ven- tilated. Quartz par- ticles, 5μ - 10μ .
" " "	2.5	Large room, good ven- tilation. Wheels en- tirely enclosed. Quartz particles mostly 20μ .
Racing sandstone.	309.5	Exhaust useless. Prac- tically all angular par- ticles, about 40μ .
" " "	25.3	Good exhaust hood.
Rumbling " castings.	210.6	60% angular particles, of up to 3μ .
Stripping large casting (steel, by hand).	91.6	6 men with hammer and chisel, 30 strokes per minute. Particles an- gular, up to 20μ .
Marble-cutting shop.	19-24	Sharp marble fragments.
Rag-sorting shop.	33-79	Textile fluff and dust.
Felt shoe factory.	175	
Cement mill.	130	Mill "not working."
" " "	224	Mill working.
Gold-mining.	188-412	Drilling quartz rock.

INTRODUCTION

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TABLE I (b).

Locality.	Number of particles per c.c.	Remarks.
Bridlington pier (5 p.m., April).	0	Gentle wind from E.N.E. Sunny and cloudless. Visibility perfect. No salt crystals and no smoke particles even in 3000 c.c. air.
Middle, Bay of Biscay (2.30 p.m., April).	15	Salt crystals up to $13\ \mu \times 0.9\ \mu$. Wind N.N.E. Visibility good.
Cheam, Surrey (8.40 a.m., July).	920	Little or no wind. Marked haze.
Westminster (May).	1,390	Ordinary non-foggy day.
Westminster (10 a.m., Feb.).	20,800	Moderate smoke fog. Buildings invisible against sky at 1600 ft.
Westminster (2 p.m., Jan.).	21,760	Dense fog. Many brownish, tarry par- ticles $1.7\ \mu$ diameter.
Westminster (11.15 a.m., Jan.).	53,000	Very dense fog, limit- ing visibility, 30- 40 yds.
Wet sandstone- grinding shop (stove grates).	496	34% particles greater than $2\ \mu$. Much scale as opaque, black par- ticles $2\ \mu$ - $10\ \mu$.
Wet sandstone- grinding shop (scythes).	3,000-3,500	Clear, translucent, yellow sand particles, from 3 to 7% over $2\ \mu$.
Wet sandstone- grinding shop (textile machin- ery large parts).	5,926	Sandstone particles of all sizes up to $10\ \mu$.
Rumbling castings (housing partly open).	3,301	31% are greater than $2\ \mu$.
Dry emery wheel grinding castings.	2,687	20% are greater than $2\ \mu$.
Racing grind- stones (to dress surface).	3,000-12,000	Up to 28% particles are coarser than $2\ \mu$. Many particles up to $10\ \mu$ and $15\ \mu$.
Gold or tin mining (drilling quartz rock).	10,000-12,000	Fine quartz dust.

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of the dust, and the size and shape of the particles.

The atmosphere in an old-fashioned flour mill, or in a rag-sorting room, appears to be far dustier than that in an iron-grinding room, particularly when viewed against a dark background, because the lighter-coloured particles reflect more light and show up in more strongly-marked contrast against the relatively dark detail beyond.

Such dusty atmospheres provide a very undesirable environment for the workers. The unhealthy character of such dusty occupations as pottery manufacture (flint dust), stone dressing (sandstone and millstone grit), the grinding of iron and steel, the drilling of quartz rock in gold and tin mines, has been recognised for centuries. In the pottery industry, the danger was understood and, generations ago, was avoided by the introduction of the wet-grinding of flint.

Towards the end of the nineteenth century, public opinion in this country was aroused by the seriousness of a number of cases of lead poisoning amongst workers engaged in the manufacture of white lead and in the glazing of pottery, and of "phossy jaw" amongst makers of lucifer matches. Between 1878 and 1895, legislation was introduced to protect the workers in certain specified industries from the incidence of such occupational diseases. Special rules were introduced into the Factory Acts to give control over dangerous occupations, with the object of obtaining early knowledge of such occupational diseases as poisoning by lead, arsenic, phosphorus and

mercury. The obligation of notifying these diseases was placed upon medical practitioners.

In the Workmen's Compensation Act of 1906, twenty-five occupational diseases were scheduled, to which the provisions of the Act applied.

Of recent years, a large amount of valuable research work has been carried out by the Home Office and by the Ministry of Health, with the object of minimising, and, where possible, eliminating, this dust hazard in industry. In many industries, steps have been taken to prevent the escape of dust from the work—as, for instance, by keeping the work wet, or by surrounding the machine with a suction hood that removes the dust as it forms. Where these remedies are impracticable, respirators have been introduced, and an increased personal cleanliness has been encouraged. In some industries, an important change has been introduced into the process itself, whereby a harmless dust is substituted for a dangerous one. The prevalence of lead poisoning in the pottery industry, owing to the inhalation of plumbiferous fume and dust arising from the use of a lead carbonate glaze, has been greatly diminished by the substitution of a lead silicate glaze that is insoluble in the gastric juice. In many cases, a great deal can be done to reduce the danger by the education of the workers themselves. This is nearly always necessary, for, even when special protective devices are introduced, they are of no use unless they are properly utilised and maintained.

Although so much has been done to minimise

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the danger to health by the introduction of suitable methods of dust prevention, there still remain occupations in which the use of such remedies are difficult to apply, either on account of the arrangement of the work or because of their effect upon the cost of the product. In industries in which general preventive measures cannot be employed, it is necessary to carry out a careful and thorough scientific investigation into the effect of the normal dust output upon the health and physical condition of the worker. From the information that is obtained in this way, it will, in most cases, be possible to devise a remedy for the disease—particularly, if it can be taken in its early stages. A periodic examination of the workers enables any diseased condition to be detected before it has proceeded too far to be remedied.

Similarly, the risk of dust explosions has been greatly lessened during recent years by the introduction of preventive measures that are based upon the results of a systematic scientific investigation of the principles underlying the ignition and combustion of different dusts. In factories and mills that were once notoriously dusty, there is a growing tendency to prevent the escape of dust by using enclosed machinery. In a modern flour mill, dust is conspicuous by its absence. The introduction of electric lighting has greatly reduced the chance of ignition by an open flame. In many cases, inflammable materials are ground and conveyed in an inert atmosphere. If an explosion or fire does occur at a point in the system, it

is prevented from spreading by the employment of ingenious dust gates and barriers, and revolving dampers, or the flame is quenched by the automatic release of inert dust. Provided that certain simple precautions are taken, it is now almost impossible for a dust explosion in a coal mine to travel more than a few yards from its point of origin.

CHAPTER II

DUST

A DEFINITION of dust as "finely divided matter" is accurate, but inadequate. The behaviour of any substance in the form of dust is so different from the normal behaviour of the substance when in a more massive form that it almost justifies a definition of dust as "a particular and distinct state of matter."

The word "dust" is of Teutonic origin, and is akin to the modern German "Dunst"—vapour. It signifies matter that is in such a finely-divided condition that it floats freely in the air and behaves like vapour or smoke. "Dust" particles may be liquid, as in mists and spray, or solid, as in many fumes and smokes. When they are suspended in air or in any other gas, they will, if small enough, acquire, in response to a ceaseless bombardment by the molecules of the gas, a mobility (Brownian motion) that is feebly reminiscent of the vigorous motion of the gas molecules themselves. The dispersed liquid or solid may thus be said to be masquerading as a gas. It appears to possess a greatly diminished density, for it floats in air; it occupies a very much greater volume; it possesses increased physical and chemical activity. It may exert a pressure upon the walls of its container. Its true solid or liquid character, however, is betrayed by its low transparency to light and heat.

Dust particles range in size from the fine sand or grit that is blown about on a windy day (0.1 mm. in diameter) to the minute particles of which cigar

smoke is made up (0.00001 mm. in diameter). The approximate diameters of different dusts are compared in the following table.

TABLE II.—Sizes of Dust Particles.

Substance.	Average diameter of particles, in cms.
Milk powder	1.4×10^{-2} to 0.7×10^{-2}
Maize starch	1.2×10^{-2}
Cement (300 mesh)	1.0×10^{-2} to 0.7×10^{-2}
Lycopodium	2.8×10^{-3}
Atmospheric fog	1.4×10^{-3} to 3.5×10^{-3}
Sulphuric acid mist from concentrators	1.1×10^{-3} to 1.6×10^{-4}
Pyrophoric carbon	1.25×10^{-4}
Pyrophoric iron	5.4×10^{-4}
Ammonium chloride fume	1.0×10^{-4} to 5.0×10^{-5}
Oil smoke (produced by detonation)	1.0×10^{-4} to 5.0×10^{-6}
Rosin smoke	1.0×10^{-4} to 1.0×10^{-6}
Tobacco smoke	1.5×10^{-5} to 1.0×10^{-6}

The rate at which dust settles in still air is directly proportional to the density of the particles and the square of their radius. Particles of sand (specific gravity, 2.5) of 0.1 mm. radius will fall with a velocity of 3.0 metres per second. Smoke particles (specific gravity, 1.0) of radius 0.00025 mm. would only fall through 3 metres in thirty days. Actually, such small particles do not settle at all, but are driven about the gas by the blows of the gas molecules with a very much greater velocity than that due to gravity.

The velocities imparted to silver particles (density, 10.5) of various sizes (*a*) by the force of gravitation, and (*b*) by molecular bombardment, are compared in Table III.

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TABLE III.

Velocity due to gravitation.	Velocity due to molecular impacts.	Radius of particles.
12×10^{-8} cm./sec.	6.3×10^{-3} cm./sec.	1×10^{-7} cm.
3×10^{-6} „	2.8×10^{-3} „	5×10^{-7} „
12×10^{-6} „	2.0×10^{-3} „	1×10^{-6} „
3×10^{-4} „	8.9×10^{-4} „	5×10^{-6} „
12×10^{-4} „	6.3×10^{-4} „	1×10^{-5} „
3×10^{-2} „	2.8×10^{-4} „	5×10^{-5} „
12×10^{-2} „	2.0×10^{-4} „	1×10^{-4} „

Owing to the very low velocity with which fine particles settle in air, they remain in suspension long enough to form a comparatively stable system. Familiar natural examples are fogs, clouds, mists, smoke. Similarly, the air in a mill or mine or above a busy street is perpetually dusty.

Any two or more phase system in which a finely divided solid or liquid is dispersed in a gas is called an aerosol. When—as in a deposit of soot, or in an accumulation of sugar dust or silica dust, for example, on a floor or wall near a disintegrator—the amount of the gas phase is relatively small, the system is called an aerogel. An aerosol may be regarded, generally, as dust in suspension, and an aerogel as dust in a heap.

It is convenient to distinguish between three kinds of industrial aerosols according to the size of particle (degree of dispersion):—

(a) *Dusts*, in which the particles are larger than 10^{-3} cm. diameter. Such particles settle in still air with increasing velocity. They do not diffuse.

(b) *Clouds*, the particles of which range in diameter from 10^{-3} to 10^{-5} cm. Such particles settle in still air at a constant velocity, depending

upon their size, according to Stokes' law. They, also, do not diffuse.

(c) *Smokes*, the particles of which range from 10^{-5} to 10^{-7} cm. diameter. Such particles are in active Brownian motion, and diffuse fairly rapidly. They do not settle at all in still air.

THE FORMATION OF DUST

Dust may be formed by the condensation of a vapour or by the disintegration of a liquid or solid.

When a saturated vapour is cooled so that it becomes supersaturated, some of it will tend to condense upon any suitable "free surface" or "nucleus" that may be in contact with it. This condensation nucleus may be the wall of the containing vessel, or a particle of dust suspended in the vapour, or a gas molecule, ionised—for example, by ultra-violet radiation—before, during or after the supersaturation of the vapour has occurred. Clearly, the character of the condensate will vary widely, according to the kind of surface upon which it forms. Upon a smooth, solid or liquid surface, it will, if it "wets" the surface, form a continuous film. On a liquid surface, a pellicle or film is formed which is broken into flakes by the movement of the liquid. If the surface tension of the condensate is high, so that it does not "wet" the surface, it will form fine particles. When a vapour condenses simultaneously upon a large number of gas molecules or ions, or upon minute dust particles suspended in it, a finely-divided condensate is produced.

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Thus, if saturated water vapour, entirely free from suspended dust or gaseous ions, and enclosed, for example, in a glass vessel, be expanded adiabatically so that it becomes cooled and, therefore, supersaturated, condensation will only occur upon the walls of the containing vessel, unless the degree of expansion is so high that condensation occurs upon molecular aggregates of the water vapour itself. If, however, the water vapour be dusty or ionised, the act of expansion is immediately followed by the formation of a fine rain or a mist, depending upon whether the condensation nuclei present are few or many.

From this, we see that, for a given degree of supersaturation, and, therefore, a given mass of vapour condensed, the degree of dispersion, or the fineness of the resulting dusty condensate, is greater, the more condensation nuclei there are present. By carrying out the condensation of the vapour at temperatures below the freezing point of water, the condensate will consist either of subcooled water droplets or ice crystals.

Many substances are prepared industrially by the condensation of a vapour. The vapour may be cooled by adiabatic expansion, or by mixing the hot vapour with a volume of colder gas. Alternatively, the vapour may be produced by a chemical reaction between two gases at a temperature at which the resulting product will be highly supersaturated. Zinc vapour burns in air to form zinc oxide, which, being very much less volatile than either of its constituents—zinc or oxygen—condenses to form a fine blue smoke, from which

the zinc oxide can be recovered by filtration. Zinc dust and aluminium dust of high quality are prepared by vaporising the metal in an electric arc, and drawing off the vapour, diluted with a large volume of an inert gas, such as nitrogen. The degree of dispersion of the product will be higher, the greater the density of the gas, the higher its pressure and the more rapid the cooling of the vapour.

Carbon black is produced by burning a hydrocarbon in an insufficient supply of oxygen. The carbon is very much less volatile than the hydrocarbon and condenses to form a dense black smoke.

In nearly every case, dust is produced in industry by the disintegration of a liquid or solid. When a substance is reduced in an attrition mill or a disintegrator, some of the fine product escapes into the atmosphere. When granular or dusty materials—*e.g.*, grain or flour—are being conveyed or elevated, the movement of the material in transit stirs up a cloud of fine dust in the immediate neighbourhood. The drilling of a rock face or the blasting of the rock in a mine or quarry necessarily produces a great deal of dust, a large part of which becomes distributed in the surrounding air. When a liquid is sprayed or atomised, it becomes disintegrated into a fine cloud or mist.

In all processes of mechanical disintegration, the different particles into which a substance is divided have to be drawn asunder against the force of cohesion. The energy that is expended in overcoming the force of cohesion is directly proportional

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to the area of new surface that is produced—that is to say, it is proportional to the fineness of the resulting product. The greater part of this energy appears as heat and raises the temperature of the product.

The degree of fineness that can be obtained by disintegration processes is limited, and is much less than that which can be obtained by the condensation of vapour. The substance may be disintegrated by the application of shearing and tensile stresses in an attrition mill, or by a crushing pressure applied gradually by means of rolls, or by sudden blows, as with impact machines of the disintegrator type.

The efficiency with which any disintegrating process can operate will depend primarily upon the rigidity with which the applied stress is received by the pieces of substance that are to be broken. As the substance gradually becomes broken down, it forms a loose dust or paste, according to whether the grinding process is dry or wet, that yields to the applied stress owing to the relative movement over one another of the loose grains of which it is composed. In all crushing operations, there comes a point at which the accumulated débris is so fine that it accommodates itself to the applied stress without the individual particles actually being stressed beyond their elastic limit. The rigidity of the mass is then too low for further crushing stresses to produce any effect. The efficiency of the process can be improved materially by removing the finer particles by a current of air or by screening, and returning the coarser constituents

to the mill. To some extent, a similar restriction is placed upon the efficiency of an attrition mill, the fine *débris* moving freely between the moving surfaces, so that the shearing stress simply imparts rotation to the individual particles instead of breaking them down.

It is comparatively easy to disintegrate a liquid, owing to its relatively low viscosity. When a liquid is projected rapidly against a solid, liquid or gaseous surface, it is stretched from the point of impact, until the resulting tension exceeds the surface tension of the liquid. The specific surface of the liquid is enormously increased, and the condition of the liquid becomes unstable; consequently, it breaks into numerous drops, each possessing a smaller specific surface and, therefore, greater stability. Similarly, if a liquid be distributed in the form of a number of fine threads—*e.g.*, by being forced through a perforated plate—the threads become unstable if their length exceeds three times the diameter, and they break up into a series of spherical drops.

Many sprays have been designed for reducing liquids such as water, oil, liquid metals, to a fine mist. These all depend for their action upon a sudden and violent collision between a jet of the liquid and either a solid surface (generally moving relatively at a high speed—*e.g.*, a rapidly rotating disc), a second jet of the liquid itself, or a jet of compressed gas. In a similar way, a bubble film breaks up into fine droplets when the bubble bursts, as in the formation of a mist during effervescence.

1012

614.71

1100

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PHYSICAL ACTIVITY

Physical equilibrium between a liquid or solid phase and the corresponding vapour phase with which it is in contact is necessarily established only by means of an interchange of molecules by the two phases across the mutual surface of contact. The more extensive this surface of contact—i.e., the greater the specific surface of the substance—the more readily will equilibrium be established. A ton of boiling water in the form of spray evaporates more readily and cools more rapidly than a ton of boiling water filling a deep tank. This surface effect is utilised in the processes of film and spray evaporation.

If the degree of dispersion be so high that the radius of the water droplets is less than 0.001 mm., the curvature is so acute that the surface molecules are less strongly held by the attraction of the internal molecules and escape more readily. The vapour tension of such small droplets is higher and, consequently, their boiling point is lower. At 0° C., the vapour pressure of water at a plane surface is 6,000 dynes per sq. cm. At the surface of a droplet of radius 0.0000016 mm., it is twice as great. Such an extremely high degree of dispersion, however, is practically never obtained in industrial operations, so that the enhanced vapour pressure of extremely fine droplets does not, at present, possess industrial importance.

ELECTRICAL CHARACTER

The electrical capacity of any substance is proportional to the area of its surface, since any

charge of electricity will reside upon the surface. When any substance is disintegrated into dust, its surface area, and, therefore, its electrical capacity, is enormously increased, particularly if the dust be dispersed in air or in any other gas. The liquid or solid particles become charged electrically, either (*a*) by the direct adsorption of ions from the gas itself, or (*b*) by contact with some suitable solid or liquid surface. Rudge suggests that in most cases the dust particles become charged by contact with one another, the sign of the charge acquired by the large particles being opposite to the sign of the charge acquired by the small ones.

(*a*) When dust is blown about by wind, it becomes charged electrically, the sign and quantity of the charge depending upon the nature of the dust and the electrical condition of the atmosphere. At the same time, the air—or extremely fine particles that are present in the air—becomes oppositely charged.

By raising a cloud of dust in a brass tube with a blast of air in such a way that the dust was blown against a fine wire-gauze basket, Rudge was able to collect the static electricity upon the basket, and to determine whether a given dust was charged, and, if so, with what sign. He investigated the behaviour of one hundred and eighty-six different samples of dust, and summarised his conclusions as follows:—

(1) Nearly all kinds of finely-divided material, when blown into a cloud of dust by a current of air, give rise to electrical charges upon the dust and upon the air.

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(2) The nature of the charge resident upon the dust particles depends upon the chemical characteristics of the material.

(3) In general, the charge obtained upon the dust is opposite to that associated with the "ion" of the same substance when in solution—*i.e.*, strongly basic bodies (*e.g.*, limestones) give negatively charged dusts, and strongly acidic bodies (*e.g.*, silica) give positively charged dusts.

(4) In the case of salts, the charge, apparently, depends on the relative strengths of the acidic and basic ions.

(5) Similarly constituted bodies give similar charges.

The charges acquired by different substances are shown in Table IV.

TABLE IV.—Charges Generated on Moving Dust Particles.

Material.	Charge.	Material.	Charge.
Carbon.	+	Dextrose.	—
Copper chloride.	+	Flour.	—
Potassium nitrate.	+	Iron.	—
Sand.	+	Iron oxide.	—
Sodium chloride.	+	Lycopodium	—
Fine soil.	+	Magnesium	—
Starch.	+	Magnesium oxide.	—
Sulphur.	+	Sodium carbonate.	—
Aluminium.	—	Zinc.	—
Aluminium oxide.	—	Zinc carbonate.	—•
Dextrin.	—	Zinc oxide.	—

Similarly, when a liquid splashes or is atomised in a gas, the increase of specific surface is generally associated with the electrification of the droplets. Thus, when large raindrops of diameter exceeding 4 mm. are flattened and ruptured by the resistance

of the air, they become positively charged, while the surrounding air becomes negatively charged. During the violent vertical circulation that occurs in a thundercloud, the positively charged droplets travelling downwards become separated from the negatively charged air that is carried upwards, so that an enormous potential difference accumulates between the upper and lower regions of the cloud. Ultimately, the tension becomes great enough for a discharge of lightning to occur.

When, in drilling for petroleum, the oil suddenly escapes through the shaft, to form a jet rising to a considerable height, a part of it is "atomised," and forms a cloud of electrically charged droplets that is remarkably stable. Frequently, discharge ultimately occurs with sufficient intensity to ignite the cloud, giving rise to the phenomenon known as the "holy fire" of Baku.

(b) Dust may also become charged as a result of friction against a solid surface. In this way, electricity is developed in disintegrators and attrition mills by the friction between the particles of the material that is being ground and the parts of the machine itself. The fine dust that escapes from the machine is electrically charged. If the machine is not earthed, it, also, becomes charged, and, in favourable circumstances, particularly in very dry weather, discharge may occur with disastrous consequences. Cohen has shown that the sign of the charge that is acquired in this way depends upon the relative dielectric constants of the dust and the material against which it rubs,

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the material that possesses the higher dielectric constant becoming positively charged.

To determine the sign of the charge acquired by sugar dust, when agitated in air, an insulated cylinder of fine-mesh copper gauze was connected with an electrometer. When the electrometer was charged positively, and then, by means of a fine capillary tube, sugar dust was blown into the gauze cylinder from a distance of 5-10 cms., the charge upon the electrometer was increased. When the electrometer was charged negatively, the sugar dust reduced it. When the electrometer, previously uncharged, was charged positively by blowing sugar dust into the gauze cylinder, it was discharged by blowing aluminium dust into the cylinder, showing aluminium dust to be negatively charged in air.

It was found that, when 10 mgms. of sugar dust was blown into the cylinder from a distance of about 5 cms., the electrometer acquired a charge of over 200 volts.

Beyersdorfer found that the charge acquired by 1 gram of sugar dust, after passing through a copper tube of 1 mm. bore, amounted to 8.5×10^4 e.s.u. By calculating approximately the number of particles that would come into actual contact with the wall of the tube, he found the average charge per particle to be 420 electrons, which is of the same order as the charge upon the particles of a hydrosol.

The stability of an aerosol, like that of a hydrosol, is frequently due to the presence upon the particles of charges of the same sign. The introduction of oppositely charged ions into a hydrosol

reduces the potential difference between the particles and the dispersion medium, until the iso-electric point is reached and flocculation results. Similarly, under suitable conditions, an aerosol may be flocculated by gaseous ions, or by introducing dust particles carrying charges of the opposite sign.

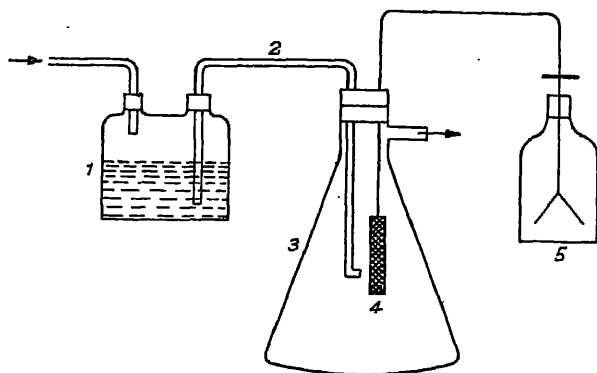


FIG. 1.—EXPERIMENTAL ARRANGEMENT FOR DETERMINING THE CHARACTER OF THE ELECTRIFICATION OF DUST CLOUDS.

Beyersdorfer has investigated very fully the electrification of sugar dust. His apparatus, which is similar to that used by Rudge, is shown in Fig. 1.

A glass bottle, 1, filled with finely ground sugar, is connected by the tube, 2, with the suction flask, 3. In this flask, a cylindrical electrode, 4, is placed, in such a position that the dust that enters the flask will impinge upon it. The electrode is connected with an electroscope, 5.

The sugar dust was blown into the flask by a

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blast of dry, compressed air (2 atmospheres). The glass tube became positively charged, the sugar negatively charged, in accordance with Cohen's law, the dielectric constants of sugar and glass being, respectively, 3.32 and 6-10. By substituting an insulated copper bottle and tube for the glass, the sugar became positively charged, and the copper negatively charged. The copper vessel became so strongly charged that a strong spark of up to 1 cm. in length could be drawn from it, corresponding to a potential of 25,000 volts.

It will be seen, therefore, that, in practice, charges of over 10,000 volts can readily be accumulated. Such charges are frequently found upon the filter bags that are used to separate the sugar dust from the air. These bags act as a kind of electrical machine, separating the positively charged dust from the negatively charged air. Similar charges have frequently been observed in threshing machines, in attrition mills, and in cotton gins. Unless steps are taken to prevent the accumulation of static electricity by humidifying the air, or by introducing suitably earthed collectors, there is every likelihood of the dust being ignited by a spark discharge.

When steam is discharged through a narrow orifice, the droplets of water in the resulting cloud are found to be positively charged, the orifice negatively charged. This fact forms the basis of Armstrong's hydro-electric machine. No electricity is produced with perfectly dry steam. None is produced if the steam contains

certain impurities, or if the orifice is made of an unsuitable material—*e.g.*, ivory. Faraday attributed the production of electricity to the friction between the water droplets and the walls of the orifice. Similar effects are obtained when moist air or dusty air is used.

If a readily inflammable dielectric such as ether, benzene, or petrol, becomes electrically charged in this way—for example, by friction against an insulated metal container from which it is flowing—it may produce an electric spark and become ignited. Similarly, an inflammable gas—*e.g.*, hydrogen—may be ignited by sparks produced by the discharge of dust particles suspended in the gas, that become charged by friction with a suitable pipe or valve through which the dusty gas is flowing.

The enormously increased electrical capacity of matter in a finely-divided condition is a frequent contributory cause of the explosion of combustible dust.

ADSORPTION OF GASES BY DUST PARTICLES

When any gas or vapour is in contact with any solid or liquid surface, some of the molecules of the gas or vapour will condense upon the solid or liquid surface. A proportion of these condensed or absorbed molecules will re-evaporate, but, generally, the rate of condensation exceeds the rate of re-evaporation, so that, under the given conditions, a layer of gas remains permanently adsorbed upon the surface. The solid surface becomes coated with a thin film of adsorbed molecules. Gradually, and to a limited extent, they

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will diffuse into the interior of the solid. The molecules that condense upon a liquid surface will, owing to the intermolecular freedom and mobility of a liquid, diffuse rapidly into the body of the liquid until it becomes saturated with them. Not until then will a permanent film of adsorbed molecules be formed upon the liquid surface.

Adsorption is specific and selective, and, under given conditions of temperature and pressure, will vary with the nature of the gas, and the nature and physical state of the adsorbing surface.

Generally speaking, the more condensable a gas is, the more readily will it be adsorbed at a given surface. Thus, carbon dioxide and the vapours of water and of various organic solvents are more readily adsorbed than oxygen, nitrogen and hydrogen.

A given gas will be adsorbed more readily, the higher the pressure and the lower the temperature.

Since adsorption is essentially a surface phenomenon, the amount of gas that will be adsorbed by a given mass of solid or liquid will be proportional to the area of the adsorbing surface—*i.e.*, to the specific surface—or to the degree of dispersion of the adsorbent.

It often depends, to an even greater extent, upon the physical character or texture of the surface. A micro-cellular structure not only offers a greater total surface to the gas, but, owing to the capillary action of its minute pores or cells, it will adsorb gases more readily than would a smooth, compact surface of the same material. Fine liquid or solid dust particles, therefore—particularly if they are of a porous character—adsorb gases freely.

Frequently, the volume of gas adsorbed is very much greater than the volume of the dust upon which it is adsorbed. Thus, a litre of carbon black may contain 950 c.c. of adsorbed air, which, at normal temperature and pressure, would occupy 2.5 litres, and only 50 c.c. of actual carbon black.

Many substances—for example, precipitated SiO_2 , MgCO_3 , ZnO —when reduced to fine powder (300 mesh), will flow and surge like a liquid, the particles being cushioned by adsorbed gas, and, therefore, able to move freely over one another.

Beyersdorfer has shown that, if 200 grams of lump sugar is ground for twenty-four hours in an air-tight ball mill, the pressure of the air in the mill is reduced from 760 mm. to 23 mm., owing to the adsorption of air upon the freshly formed sugar surfaces.

When the particles of an aerosol are cushioned by adsorbed gas, they are less able to come into contact with one another to coalesce to form larger particles. Consequently, the aerosol is more stable. When, under suitable conditions of concentration, temperature and electrical charge, the aerosol becomes flocculated, the particles form loose aggregates or “flocks” of the corresponding aerogel. Such flocks are formed by the zinc oxide smoke from a brass foundry, or by carbon smoke as it forms soot on the wall of a flue.

CHEMICAL ACTIVITY

The rate at which two given substances react chemically depends, *caeteris paribus*, upon the

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facility with which they can be brought into contact with one another. Consequently, the rate of reaction is highest when two gases react, less with liquids, and least with solids. At any given moment, chemical reaction is necessarily restricted to those molecules that are actually situated at the surface of contact. Consequently, the reactivity of any substance is a function of its specific surface. In one sense, a gas has no surface; in another sense—in the freedom of its molecules to react—all the molecules of a gas are surface molecules, *i.e.*, a gas is all surface.

The surface of a liquid, as we have seen, can be enormously increased by spraying or by the formation of thin films. Similarly, the specific surface of a solid can be increased by disintegration. Not only will reaction occur more rapidly between two substances in powder form, but it will also occur more readily, for instance, at a lower temperature. Finely-divided iron and sulphur, when ground together in a mortar, combine at the ordinary temperature. Extremely fine iron or lead dust becomes incandescent when exposed to the air.

The chemical reactivity of any substance, therefore, is increased by disintegration in two ways :—

(1) Owing to the greater specific surface, a given reaction can occur more rapidly.

(2) Owing to the resulting greater surface energy of the individual particles, they can react more readily.

So great is this effect that many substances

that, in a comparatively massive condition, burn in the air with difficulty, can, when dispersed in the air in the form of dust, burn with explosive violence. Of the many industrial substances that form explosive dusts, some of the most readily inflammable are sugar, dextrin, starch, coal, cocoa, rice, malt, flour, maize and tea.

THE STABILITY OF AEROSOLS

When dust particles are suspended in a gas to form an aerosol, they are in a condition of unstable equilibrium. Gradually, they will be removed from the gas, either (a) by settling, (b) by deposition upon the walls of the container or upon other solid or liquid surfaces, or (c) by diffusion.

For particles of diameter less than 10^{-5} cm., the molecular bombardment to which they are subjected will, at the ordinary temperature and pressure, effectively prevent them from settling from the gas. An exceedingly small fraction of these particles will come into contact with, and adhere to, the walls of the container. The removal of the particles by this means can be accelerated by stirring, whereby more particles are brought, in a given time, into contact with the walls of the container and with one another. The increased collision frequency of the particles leads to the formation of relatively coarse aggregates or "flocks," which settle rapidly. The removal of the particles by settling can obviously be greatly hastened by introducing a number of suitable surfaces into the gas itself, so that, at

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at a given moment, all the particles are sufficiently near to a suitable depositing surface to diffuse or to be carried by convection currents towards it in a reasonably short time.

This is the principle underlying the filtration of aerosols such as smokes and dusty gases. The aerosol is passed through a fine, cellular fabric—for example, cotton or woollen cloth—the passages through which are so small that, while the aerosol is passing through the filter, the suspended particles diffuse to, or are thrown by eddy currents towards, the walls of the passages and become deposited there. The particles are deposited upon the surface of the fibres of the cloth in a similar way, as the aerosol passes over them.

The removal of the suspended particles by simple settling can be greatly increased if the particles can be induced to form large aggregates or flocks. The natural tendency of an aerosol to form such flocks is frequently inhibited by the presence on the particles of films of adsorbed gas, or of electrical charges of like sign. Adsorbed gas can sometimes be displaced by introducing a more readily adsorbed vapour—*e.g.*, water vapour—into the aerosol, or by forcing the particles into violent contact with a baffle or with one another, in order to displace the adsorbed gas film mechanically, to a sufficient degree to permit the particles to come into contact.

The increase of stability that is due to the particles carrying electrical charges of the same sign can be overcome by introducing particles that are charged oppositely, so that attraction and aggre-

gation are induced, or by subjecting the aerosol to a suitable potential gradient, so that the charged particles travel in the same direction and are ultimately deposited upon one of the electrodes.

Charged or uncharged particles can be removed in this way if the applied E.M.F. is sufficiently intense to cause copious ionisation of the gas itself, for, then, the stream of ions passing through the gas from one electrode to the other charges the suspended particles, and carries them with it, and deposits them on the other electrode. This forms the basis of the well known Lodge-Cottrell process for the treatment of smokes and fumes and dusty gases.

Reference.

The properties of dust and aerosols, and the methods by which they are analysed and examined, together with the application of the information so obtained to such practical problems as the industrial treatment of fumes and dusty gases, meteorological phenomena, dust explosions, etc., are dealt with very fully in "Clouds and Smokes: The Properties of Disperse Systems in Gases and Their Practical Applications," by W. E. Gibbs. (Churchill, 1924.)

CHAPTER III

OCCUPATIONAL DISEASES DUE TO DUST

It has been recognised for centuries that certain dusty occupations are unhealthy. The workers who are engaged continually in these occupations sooner or later develop well-defined occupational diseases. In every case, the diseased condition is found to be due to the entrance of dust into the system, either by inhalation, by swallowing, or by direct absorption through the skin. In by far the greater majority of instances, the disease is due to the inhalation of the dust. The inhaled dust is partly deposited in the nose and throat; the remainder penetrates to the bronchial tubes and even to the air spaces of the lungs, particularly if the dust be very fine or if the work be so arduous as to induce deep breathing.

The persistent inhalation of certain kinds of dust induces a condition of chronic asthma or bronchitis, or, in extreme cases, leads to the development of a form of phthisis that is characterised by the growth of fibroid material around the dust that is deposited in the air spaces of the lungs. Owing to the persistent irritation of the walls of the bronchial tubes and of the lungs themselves by the dust, they become susceptible to infection by the tubercle bacillus, so that, very frequently, tuberculosis supervenes.

Metal miners, stone-masons, corn sifters, potters, iron and steel grinders, file-makers, foundrymen, textile workers, felt hat makers, amongst others, suffer from diseases of the respiratory system that are due to the inhalation of dust. Many kinds of

dust—for example, lime, salt, gypsum, starch—are soluble in the mucous membrane and are readily removed. Some soluble dusts—for instance, T.N.T. and certain compounds of lead, arsenic or mercury—are directly poisonous. It has been stated that lead poisoning can be brought about a hundred times more readily by inhaling plumbiferous dust than by swallowing it. Brass-founder's ague is directly due to the inhalation of zinc oxide fume.

In many industries—*e.g.*, cement, brick, coal—the dust, although insoluble, is without any harmful action upon the respiratory system.

Dust may also be swallowed with saliva, water or food, and either irritate the walls of the stomach and intestines, or dissolve in the gastric juices. The irritant action of fine desert sand caused a great deal of sickness amongst troops in Egypt and Mesopotamia during the War. Lead compounds, such as the carbonate and the oxide, are soluble in the acid gastric juice of the stomach as well as in the alkaline mucous membrane that lines the walls of the respiratory system. Lead poisoning is prevalent amongst lead smelters, painters, potters and the workers employed in the manufacture of white lead, and in the grinding and packing of lead paints. Direct poisoning with arsenic and mercury has been traced to the absorption of arsenic- or mercury-bearing dust in the stomach.

Finally, dust may affect the worker directly through the skin or mucous membrane. The dust may act as an irritant and produce affections of the

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skin such as eczema, furuncles, and even cancer. Certain lead compounds may be absorbed through the skin and poison the system. Some dusts—for example, quillaia bark, caustic soda—strongly irritate the mucous membrane of the eyes, nose and throat, and cause great distress. Skin diseases are prevalent amongst workers in sugar, metal, flour and certain other dusts. Sugar workers suffer to an unusual extent from dental decay. Inflammatory diseases of the eye, ear, nose or throat are unduly prevalent amongst workers in lime, cement or hair.

DISEASES DUE TO THE INHALATION OF DUST

The respiratory system consists of the nose and throat, the windpipe and the bronchial tubes, and the alveoli or air cells of the lungs to which the bronchial tubes ultimately lead. The lung resembles a large sponge in which all the air cells are connected internally by air passages (the bronchial tubes) that branch from the lower end of the windpipe. The walls of the alveoli are crowded with blood vessels, and possess a very large total area. It is through the thin walls of the alveoli that the blood is aerated.

Ample provision is made by nature normally to prevent the entrance of dust into the lung or, if it should gain entrance, to remove it from the lung. The internal parts of the nose are arranged to act as a dust filter, so that, when dusty air is inhaled, the greater part of the dust, particularly the coarser dust, is deposited on the walls of the nasal passages.

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colliers. They may also pass through the wall of the alveolus into the lymphatic vessels, and either deposit their dust in the lymphatic vessels or in the surrounding tissue, or carry it to the lymphatic glands at the root of the lungs, where they are arrested. In time, these glands become black, owing to the accumulation of dust, and, if the dust be hard—for example, quartz dust—the glands feel gritty to the knife.

In this way, normally, the lungs are able to get rid of, at any rate, some kinds of dust, even when the dust has passed the bronchial tubes and entered the alveoli.

The experiments of Arnold and Beattie have shown that little permanent injury to the lung appears to result from the inhaling of coal or shale dust, or of the soft particles of carbon smoke. When, however, such hard, inert dusts as sandstone, flint, carborundum, granite or marble are inhaled, they are not removed by phagocytic action, and the walls of the alveoli show signs of chronic inflammation. These become thickened in scattered nodules by the growth of fibrous tissue. Similar changes occur round the bronchial tubes and blood vessels. The general effect of this "fibrosis" is to stiffen and harden the lung and make it quite unfitted for respiration. Such a condition of the lung is called "fibroid phthisis." The general term by which the diseased condition of the lung, induced by dust inhalation, is denoted is "pneumokoniosis." Although this fibroid phthisis initially is not tubercular in character, it is likely to become so through ordinary infection,

The walls of the bronchial tubes are lined with a layer of epithelial cells that are provided on their free surface with multitudes of microscopic hairs or cilia; these cilia constantly wave to and fro in such a way that any liquid or solid particles that tend to become deposited upon the walls of the bronchial tubes are wafted outwards away from the lungs.

Thus, in normal circumstances, only the finest particles reach the actual air cells of the lung. More dust or coarser particles are drawn in if the breathing be deep and quick, or if, owing to recurrent colds and bronchial catarrh, the ciliated cells on the walls of the bronchial tubes have been shed, so that the protection that they afford is, for the time being, destroyed.

When dust particles reach the alveoli, they lie free at first, but are soon absorbed by living cells (phagocytes) that belong to the epithelial layer of the alveolus or have wandered through the thin wall of the alveolus from the blood. These phagocytes, or dust-absorbing cells, continue to collect dust particles until they appear to be full, the other cells remaining dustless. Some of the phagocytes remain attached to the wall of the alveolus; others become free and, if there is much dust, may be sufficiently numerous to fill the alveolus.

The phagocytes are endowed with a certain amount of mobility; they pass outwards into the bronchial tubes. They then pass up the bronchial tubes and are removed by coughing. These form the basis of the well known "black spit" of

the tubercle bacillus becoming grafted on to the chronically inflamed walls of the alveoli.

Thus, the effect of dust upon the lungs differs widely with different dusts. The specific action of various different dusts is reflected in the figures in Table V, showing the mortality from phthisis and other diseases of the respiratory system in different trades.

TABLE V.

Occupation.	Com- parative mortality figures. (All causes.)	Mortality figures.	
		Phthisis.	Other diseases of res- piratory organs.
Agricultural. . . .	602	106	115
Pottery; earthenware manufacture	1706	333	668
Cutler (grinding) . . .	1516	382	518
File cutter	1810	402	423
Glass maker	1487	295	445
Copper worker	1381	294	406
Iron and steel manu- facture	1301	195	450
Stone quarries	1176	269	307
Brass worker	1088	279	273
Chimney sweep	1311	260	291
Lead worker	1783	148	397
Cotton manufacture . .	1141	202	338

There is no doubt that the high mortality in such trades as steel grinding, file cutting and pottery manufacture is due mainly to the injurious character of the dust that is inhaled.

It is instructive to compare the death-rate from phthisis in different mining industries. Table VI shows very clearly the profound difference that exists between the action of coal dust, and that

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of fine quartz dust that is produced in the drilling of the rock in a tin mine. On the Rand, miner's phthisis is chiefly prevalent amongst rock drillers. In dry mines, the drilling, blasting and shovelling of the rock all produce dust; this dust consists of sharp, siliceous particles.

TABLE VI.—Death-rate from Phthisis.

Occupation.	Death-rate.
Mining industry	109
Coal mining	97
Ironstone mining	90
Tin mining	508
Lead mining	380
Other occupations (males) stated as.	100

It is estimated that a miner, when working at the rock face, will inhale from 2 to 3 grams of dust per hour. For men working in such a dusty atmosphere, the average working life, until quite recently, was nine years, while the average age at death was under thirty-five. A dried lung from a Rand gold-miner was found to contain 4.47 per cent. by weight of silica, the great majority of the particles averaging about 0.001 cm. ($1\ \mu$) in diameter, comparatively few being more than 0.01 cm. ($10\ \mu$). Similar siliceous dust is produced during the mining and grinding of ganister and in the manufacture of ganister bricks; also, in working sandstone and in grinding iron and steel on sandstone grinding-wheels. "Potter's rot" is due to the inhalation of fine flint dust.

The inhalation of quartz dust in gold-mining has been greatly diminished of recent years by the use of "wet drills," in which a jet of water is

directed upon the point at which the rock is being drilled. The mines are better ventilated, so that the dust does not accumulate in the atmosphere in the neighbourhood of the drills. By carrying out a systematic X-ray examination of the workers—particularly, those who are engaged in rock drilling—it is possible to detect the accumulation of dust in the lungs before it has become acute. In many cases, successful attempts have been made to stimulate phagocytic action and clear the lungs by the inhalation of dust, such as coal dust that stimulates phagocytic action.

Dusts such as coal, limestone, pure clay and gypsum do not produce a corresponding effect upon the respiratory system. Apparently, the harmlessness of the dust depends upon its power to excite phagocytic action. The dangerous character of silica dust is due less to its hardness and sharpness than to its inertness in the presence of phagocytes.

It is found that, when a dust—for example, coal dust—that is readily removed by phagocytic action, is inhaled along with silica dust, the silica as well as the coal dust is removed by phagocytes. In some coal mines in which as much as 70 per cent. of siliceous dust from adjacent rock seams becomes mixed with the coal dust, the mortality from phthisis is strikingly low. It has been suggested that, in places in which it is impossible to prevent the inhalation of silica dust, the harmful effect of the dust might be minimised or even prevented by mixing with it a dust, such as coal dust, that readily excites phagocytic action.

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When the part played by dust in causing these diseases of the respiratory system was realised, various methods were introduced to prevent the inhalation of the dust. As a result, the incidence of disease from such causes to-day is in some industries practically eliminated, and in others very greatly reduced. The first method of prevention was to introduce the wearing of respirators by workers; it was found, however, that, in designing a respirator to prevent the passage of dust into the nose and mouth, it is almost impossible to obtain efficient filtration and, at the same time, permit free breathing. Some of the box-type respirators that were used during the War against toxic smokes would, no doubt, be efficient, but it is difficult to induce men to wear them constantly when at work; they are clumsy things and tend to become very hot and uncomfortable. A great part of the dust can be filtered by the use of dry or moist fabric respirators, made of flannel or other fluffy material, but even these simple devices do not find favour with the workers.

In many industries—for example, in rock drilling in a mine—attempts have been made to prevent the dust rising from the work by keeping the work wet; in some cases, this proves to be a satisfactory expedient, but in other cases, as, for instance, in grinding metal parts on a grindstone, wet grinding seems to produce almost as much dust as dry grinding.

A very comprehensive and instructive report has recently been published by Messrs. Macklin and Middleton upon the effects of dust inhalation

upon workers engaged in the grinding of metals and the cleaning of castings. They show that the greater proportion of the siliceous dust is produced during the racing, rodding or hacking of the grindstones, and that, in many cases, the use of water to keep a grindstone wet does not by any means prevent the escape of dust into the surrounding air. They recommend that the only satisfactory method of preventing the escape of dust is to surround the grindstone with a hood, connected to an efficient exhaust. They also recommend that, where possible, the use of sandstone should be discontinued, and manufactured wheels of emery be used, instead. It is found that, with such manufactured wheels, used wet, the amount of dust evolved is very much less, and is of such a character that it can be safely disregarded. In the cleaning of castings, siliceous and other dusts are produced by the knocking-out of cores, etc., the brushing-off of the adherent sand, and the grinding of the surface of the castings to remove excrescences. These operations are performed either by hand or power-driven tools, by dry manufactured wheels, by sand-blasting, or in mechanically-revolved rumblers.

Messrs. Macklin and Middleton state that: "The dust may be suppressed wholly or partially by localised exhaust ventilation, by damping the floor of the cleaning room, and by frequent cleansing of the room, plant and fixtures. In this connection, the use of gridded benches for cleaning, with enclosed spaces beneath connected to an exhaust system, is recommended, as is also the

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provision of gratings in the floor of the cleaning room. Close-fitting doors for sand-blasting rooms and chambers are essential, and operatives at sand-blasting plant should be provided with efficient protective helmets, gauntlets and overalls."

LEAD POISONING

Of the directly poisonous dusts, the most widely prevalent are those of certain lead compounds, particularly the oxide, carbonate and the chromate. Plumbiferous dust and fume are produced in large quantities during the smelting of lead ores and in the manufacture of red lead. Lead oxide and sulphate dust are formed during the cleaning of the smelter flues. Lead carbonate dust is raised during the stripping of the beds in the manufacture of white lead. Lead-bearing dust is also formed during the manufacture and grinding of such paint materials as lead carbonate and chromate. Lead carbonate fume is produced in pottery manufacture when the lead carbonate glaze is being applied. Lead-bearing dust is also formed when paintwork containing lead paint is rubbed down.

The dust is readily absorbed by the alkaline mucous membrane. Some dust passes into the stomach and is dissolved by the gastric juice. Soluble lead compounds can also be absorbed through the skin.

In recent years, the prevalence of lead poisoning in some industries has materially diminished, while in others there is little, if any, improvement. This is shown by the figures in Table VII, giving

the numbers of cases of lead poisoning in different industries in three typical years.

TABLE VII.—Lead Poisoning.

Industry.	Year 1900.	Year 1904.	Year 1913.
White lead . . .	358	105	29
Pottery . . .	200	96	62
Paints and colours . .	56	43	22
Coach-painting . . .	70	60	71
Ship-painting . . .	32	48	31
Lead smelting . . .	50	41	49

It will be noticed that a very great improvement is evident in the first three industries; this is to be attributed partly to the introduction of exhaust ventilation. In the pottery industry it is due, also, to the introduction of a lead glaze (lead silicate) that is insoluble either in the mucous membrane or in the gastric juice. In the manufacture of white lead, the improvement is due largely to the introduction of labour-saving devices, which greatly diminish the amount of direct handling which is necessary. In such occupations as coach-painting, ship-painting and lead smelting, it is difficult to remove the dust as it forms. Of recent years, however, the use of a special "wet" sandpaper for rubbing down has led to a marked diminution in the amount of dust that is set free, with a corresponding improvement in the health of the workers. In many cases, the risk of inhaling the dust can be lessened very much by the introduction of improved ventilation; the dust, as it is formed, is carried away from, instead of being allowed to drift towards, the worker.

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When the dust of such poisonous substances as trinitrotoluene and the lead compounds already mentioned becomes deposited in the clothing and upon the skins of the workers, it becomes absorbed and the workers become poisoned. During the War, many munition workers were poisoned by the T.N.T. dust that was raised during the filling of shells. Poisoning, at first, was attributed to inhalation, and steps were taken to prevent it by the use of respirators. It was shown, however, that T.N.T. was absorbed through the skin, and that its effect could be prevented simply by insisting upon the systematic cleanliness of the workers. In the following table are shown the number of cases of toxic jaundice, due to this cause, notified to the Chief Inspector of Factories for each quarter of the three years 1916-18. The effect of the introduction of preventive methods is shown in the rapid fall that set in in the middle of 1917.

TABLE VIII.

Year.	Quarterly figures.			
	1.	2.	3.	4.
1916 . . .	6 ⁴	16 ⁵	73 ²¹	86 ²³
1917 . . .	83 ¹²	56 ²⁰	21 ⁸	29 ⁴
1918 . . .	13 ⁴	6 ²	5 ²	10 ²

(The small figures show fatal cases, which are included in the large figures.)

In all occupations in which such poisonous dust necessarily comes into contact with the skin of the worker, its effects can only be minimised by insisting upon the workers taking daily baths, changing

their clothes frequently, and generally maintaining habits of the utmost cleanliness.

Dust may, at times, contain pathogenic organisms which, coming into contact with the skin, or being inhaled or swallowed, may cause infection. Perhaps the best known instance of this is the occurrence of anthrax infection amongst workers in hides and raw wool. The number of cases of anthrax amongst wool-workers during various successive five-yearly periods is shown in the following table (Table IX).

TABLE IX.

	1901-5.	1906-10.	1911-15.	1916-18 (3 yrs.)
Wool-workers .	98 ²⁰	130 ²¹	164 ²²	198 ²³

The use of downwards exhaust ventilation for twenty-five years has not by any means removed the risk of infection. It would seem that the only way to do this is to destroy the anthrax spores before the infected material is handled by the workers. This is a difficult problem, since anthrax spores are very resistant. They can be destroyed by exposure to saturated steam at 100° C., but this process would also destroy the wool. Recently, attempts have been made to sterilise the wool by means of formaldehyde, and it would seem that this method is meeting with success. The reduction in the proportion of fatal cases, as shown by the small figures in the table above, is due to the introduction of an anti-anthrax serum.

From this general summary of the risks to health that are associated with various dusty occupations,

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it is clear that, although a great deal has been done to improve working conditions, much still remains to be done before such risks can be completely eliminated. It is necessary to study the action of the different dusts upon the respiratory and other organs, and to observe and record the effect of these dusts upon the health and physical condition of the workers. By carrying out a systematic medical examination of the workers in a dusty occupation, it is generally possible to detect the effects of dust at an early stage, and, by applying suitable remedial measures, to prevent the development of the corresponding occupational disease. In many cases, a suitable treatment for the disease, even at its early stages, still remains to be worked out. A great deal can be done in some occupations to minimise the amount of dust that comes into contact with the workers, by improving the methods of ventilation, by devising better manufacturing processes, and by altering the design and disposition of plant and machinery.

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CHAPTER IV

EXPLOSIVE COMBUSTION

ANY chemical reaction takes place in at least two stages—it begins and it continues. The necessary conditions, for example, of temperature or pressure are induced at a point, or points, in the system, and are then communicated progressively to the other parts of the system.

For any substance to burn in air, it must first be ignited—*i.e.*, at some point, its temperature must be raised sufficiently for molecules of the combustible to react with neighbouring molecules of oxygen, with the evolution of heat. The heat set free is partly lost by radiation and convection, and as sensible heat in the products of combustion, and partly in heating the adjacent layer of the combustible. If, by this means, this layer of combustible is heated to the ignition point, it, also, will burn and evolve heat. In this way, ignition will be propagated throughout the mass of combustible, and the reaction will continue. The spread of combustion may be arrested by preventing the temperature of the unburnt material from reaching the ignition point, either by absorbing some of the heat of combustion, as, for example, by the wire gauze of the Davy safety lamp, or by diminishing the rate of combustion—for instance, by reducing the oxygen content of the air by dilution with an inert gas.

The velocity with which combustion proceeds depends upon the temperature and extent of the source of the primary ignition, and then upon the rate at which molecules of the combustible and

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of oxygen come into contact with one another under conditions which promote combination. It is increased by raising the temperature or pressure, or by using a source of ignition with a larger effective heating surface. It can be accelerated, also, by moving the air over the surface of the combustible, or by increasing the concentration of oxygen in the air, or by increasing the surface that is freely exposed by the combustible to the air. A fire burns better in a good draught, provided that the air velocity is not sufficient to quench it by withdrawing heat more quickly than it is generated. Wood shavings burn very much more rapidly than a block of wood of equal weight; sawdust, provided that the particles have free access to the air and are not too far apart to communicate ignition to one another, burns even more rapidly; a cloud of fine wood dust will burn with a correspondingly greater velocity. Also, owing to the small size of the particles, such finely-divided material can be ignited much more readily.

The greatest specific surface, and, therefore, the maximum possible surface of contact, between a combustible and air is obtained when the combustible is a gas. In such a mixture, all the molecules, both of the combustible and of the atmospheric oxygen, are readily available, so that, if the gas and the oxygen are present in suitable proportions—approximately, their combining proportions—combustion, once it is initiated, will spread through the gas mixture at a very high velocity.

IGNITION

The constituents of the gas mixture react with one another at much lower temperatures than that at which flame occurs. The rate of reaction is then much slower, so that heat is lost by radiation and conduction almost as rapidly as it is produced by the reaction. As the temperature rises, the reaction proceeds more rapidly, and the heat of reaction is generated more rapidly, until, at a sufficiently high temperature, it is sufficiently in excess of the heat that is lost by radiation and conduction to raise the temperature of the adjacent layer of gas sufficiently for it to ignite. Ignition then becomes propagated throughout the mixture. The temperature at which this occurs is called the ignition temperature.

Clearly, the ignition temperature is not necessarily the temperature at which flame appears. Flame occurs only when the heat of reaction is sufficiently intense to produce visible radiation. Generally, a definite period of time—the pre-flame period—intervenes after ignition, before the temperature of the reaction reaches this value.

In determining the ignition temperature, it is necessary to define the manner in which heat is conveyed to the gas mixture—for example, the area of the heating surface, and the duration of contact. A large source of heat, acting for a relatively long time, such as an open flame, will generally ignite the gas mixture at a lower temperature than a hotter, but smaller, source of short duration, such as an electric spark.

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The minimum temperatures at which certain gas mixtures are immediately ignited by momentary contact with a relatively minute hot body are compared in Table X.

TABLE X.

Gas. (Mixtures with air.)	Minimum temperature of hot body required for immediate ignition by momentary contact. Deg. cent.
Hydrogen	747
Coal gas	878
Carbon monoxide	931
Ethylene	1000
Petrol (fraction 0—80° C.)	995
Ether	1033
Benzene	1062

A gas mixture may be ignited by compression—or, rather, by the rise of temperature that is produced by compression. Mixtures of oxygen and hydrogen can be ignited by compressions of from 1 to 30—40 atmospheres. Once initiated, combustion occurs very much more rapidly in a compressed gas mixture, owing to the higher concentrations of the reacting gases.

THE PROPAGATION OF IGNITION

Ignition can only be propagated through the gas if the heat of combustion of the mixture at any point is sufficiently intense to raise the temperature of the adjacent layer of the mixture to the ignition point. The intensity of the heat that is generated by the ignition of the gas will depend upon the heat of reaction and the rate of the reaction. For a given gas, the rate of reaction will be greater the

higher the temperature, and the more closely the composition of the mixture approximates to the combining proportions of the constituents.

A higher ignition temperature, by accelerating the rate of the initial reaction, leads to a more rapid production of heat, thus facilitating the combustion of the adjacent layer of gas.

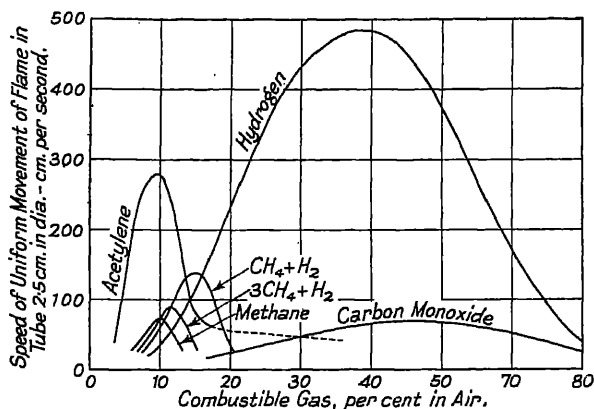


FIG. 2.—VELOCITY OF UNIFORM MOVEMENT OF FLAME IN VARIOUS GAS MIXTURES.

THE VELOCITY OF UNIFORM MOVEMENT

When the gas mixture is ignited without shock, and in circumstances that permit the free expansion of the burning gases, uninfluenced by the resulting pressure waves, combustion spreads through the mixture with a uniform velocity. This velocity of uniform movement for a number of different gases, burning in a tube of 2.5 cms. internal diameter, is shown in Fig. 2. The velocity is greater in wider tubes. The highest velocities are

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obtained in mixtures containing the gases approximately in their combining proportions. As the concentration of inflammable gas departs from this value in either direction, the velocity of uniform movement becomes smaller until, at an upper and lower limit of concentration, it is practically nil. When the proportion of combustible gas lies outside these limits, combustion only occurs within the immediate vicinity of the source of ignition, producing a cap or aureole round it.

LIMITS OF INFLAMMABILITY

The limits of inflammability for a number of gases and vapours, mixed with air at the ordinary temperature and pressure, contained in a 2½-litre sphere and ignited at the centre, are given in Table XI.

TABLE XI.

Gas or vapour.	Volumes of gas or vapour per cent. of mixture.	
	Lower limit.	Upper limit.
Methane	5.6	14.8
Ethane	3.1	10.7
Pentane	1.4	4.5
Acetylene	3.3	52.3
Benzene	1.5	5.6
Methyl alcohol	6.5	24.0
Acetone	2.25	9.6
Petrol	1.1	3.8

THE PROGRESS OF COMBUSTION

The heat of combustion causes the burning gas mixture to expand. This expansion is very small in limit mixtures; it increases rapidly as the concentration of inflammable gas approaches the

optimum value. The sudden expansion of the gas sets up a pressure wave, which travels through the gas mixture with the velocity of sound in all directions from the point of ignition, and, therefore, precedes the flame. A succession of such high-velocity pressure waves is projected in all directions from the front of the advancing wave of combustion or flame. If this pressure wave is reflected from some obstacle, so that it travels back to meet the wave of combustion, it will at first check the advancing flame, but since, at the same time, it will compress the burning gas mixture and the unburnt gas ahead of it, it will greatly accelerate the rate of combustion, and, therefore, the flame velocity.

The passage of the flame leaves a trail of hot reaction products, that immediately begin to cool and contract. The resulting reduction of pressure checks the progress of the flame, and, if sufficiently great, will cause it to reverse its direction. If the gas mixture be burnt in a glass tube, the flame will initially be seen to travel slowly along the tube at a uniform speed, and will then begin to swing backwards and forwards along the tube, in response to a series of alternating compressions and rarefactions, with oscillations of increasing amplitude. The more rapidly the gas mixture reacts, the more readily will this oscillation of the flame be set up. The velocity of the flame during this oscillatory movement is of the order of 700 metres per second.

THE DETONATION WAVE

When combustion occurs so rapidly that the pressure wave compresses the unburnt gas mixture

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to its ignition point, the flame velocity is enormously increased, and a detonation wave is set up. The detonation wave differs from the oscillating wave that precedes it in the intensity and rapidity with which combustion occurs in the wave front. The detonation wave may be regarded as a single intense oscillation, traversing the whole mass of the gas. Its velocity depends upon the heat evolved in the combustion, the specific heats of the gases, and the density of the mixture, and, for a given gas mixture, has a constant value. The velocity of this detonation wave in different gas mixtures is shown in Table XII.

TABLE XII.—Rates of Explosion for Mixtures
Fired at 10° C. and 760 mm.

Mixture.	Metres per second.
$2\text{H}_2 + \text{O}_2$	2820
$\text{H}_2 + \text{Cl}_2$	1729
$2\text{CO} + \text{O}_2$ (moist, saturated at 28)	1703
$\text{NH}_3 + 3\text{O}_2$	2390
$\text{CH}_4 + 2\text{O}_2$	2322

In a given gas mixture, therefore, the primary ignition sets up a heat wave, which travels relatively slowly and propagates ignition to the unburnt gas. This is followed by a wave of combustion or flame. The pressure wave, travelling with the velocity of sound, precedes the ignition wave and compresses the gas in front of it. This accelerates the combustion of this gas when it becomes ignited, and thus increases the velocity of the ignition wave. The wave of combustion leaves a region of partial vacuum behind it, which ultimately

leads to the reversal of the wave of combustion or flame. If the intensity of the pressure wave is high enough, a detonation wave is set up which travels through the gas mixture with about twice the velocity of sound. The shattering effect of the explosion, as distinct from the bursting action of the expanded gas, is due to the impact of such high-velocity detonation waves.

THE EXPLOSION PRESSURE

The expansion pressure that is developed by the combustion of a gas mixture in a confined space is due either to the heating and expansion of the gas, or to the formation of gaseous reaction products. It is clear, therefore, that the maximum pressure that is developed will depend upon the rate of combustion, and, for a given gas, will be a criterion of the inflammability of the mixture. This is shown by the results of Sir Dugald Clerk's

TABLE XIII.—Oldham Coal Gas and Air Mixtures.

Temp. of gases before ignition, 17° C. Pressure of atm., 14.7 lbs.

Experi- ment.	Proportion of gas by volume.	Maximum pressure in lbs. per sq. in. above atmos.	Maximum tem- perature, degrees cent.	Time of explosion, seconds.
A	$\frac{1}{15}$	40.0	806	0.45
B	$\frac{1}{12}$	51.5	1033	0.31
C	$\frac{1}{10}$	60.0	1202	0.24
D	$\frac{1}{8}$	61.0	1220	0.17
E	$\frac{1}{6}$	78.0	1557	0.08
F	$\frac{1}{4}$	87.0	1733	0.06
G	$\frac{1}{3}$	90.0	1792	0.04
H	$\frac{1}{2}$	91.0	1812	0.055
I	$\frac{2}{3}$	80.0	1595	0.16

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experiments with mixtures of Oldham coal gas and air (Table XIII).

The mixture that exploded the most rapidly developed the greatest maximum pressure and the highest maximum temperature.

Similarly, in all other forms of explosive combustion, the maximum pressure that is developed is determined by the velocity with which the reaction proceeds. The explosion pressure may be developed (*a*) by the rapid expansion of a body of gas by the heat of combustion, or (*b*) by the rapid production of a sufficiently large volume of gas, either by the combustion of a liquid or solid combustible, or by the sudden decomposition of a highly unstable chemical compound. Liquid or solid combustibles in a massive condition burn too slowly to produce an explosion unless they are readily volatile at the temperature of ignition, and then the vapour that is formed may burn rapidly enough to be explosive. It is only when the liquid or solid is reduced to a finely divided condition, and is mixed intimately with a suitable volume of air, that combustion is rapid enough to be explosive.

THE COMBUSTION OF AN AEROSOL

An aerosol necessarily possesses a very much coarser structure than a gas mixture. Consequently, the processes of ignition and propagation occur more slowly. On the other hand, an aerosol frequently contains a greater mass of combustible per unit volume than there is in a gas mixture, so that the quantity of heat that is generated by

the combustion of an aerosol, and the volume of the gaseous combustion products that are formed, may be considerably greater than those that result from the combustion of a gas mixture. Some conception of the pressures that may be developed by the explosion of equal volumes of a dust cloud and a gas mixture may be gained from the following calculations. In the first instance, the pressure that can be produced by the combustion of one gram of sugar dust, dispersed in just sufficient air for complete combustion, is calculated, assuming that reaction is carried out at constant volume. In the second case, the maximum pressure is calculated that can be developed by an equal volume of a mixture of methane and air in their combining proportions, when exploded at constant volume. In both cases, it is assumed that no heat is lost by radiation or conduction during the reaction and, further, that the reaction proceeds completely and instantaneously.

(1) One gram of sugar, dispersed in 3.71 litres of air at N.T.P., will yield, after combustion, 6.12 grams of gas, consisting of nitrogen, carbon dioxide and water vapour. At N.T.P., this quantity of gas will occupy 4.65 litres. The heat of reaction, assuming the reaction to occur so rapidly that no heat is lost by radiation, will be 3950 gram/calories. This will be sufficient to raise the temperature of the reaction products to 4300° C.

If we assume that the volume of the reaction products is increased by one two-hundred-and-seventy-third part for each degree rise of tempera-

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ture, the final volume of gas at constant pressure will be

$$\frac{4.65 \times 4300}{273} = 73.2 \text{ litres.}$$

Thus, the maximum theoretical pressure that can be produced by the combustion of 3.71 litres of dusty air, containing 1 gram of sugar dust, is $\frac{73.2}{3.71}$ atmospheres—that is, 19.7 atmospheres.

(2) 3.71 Litres of a mixture of methane and air in their combining proportions will give, on explosion, 3.71 litres of a mixture of carbon dioxide, water vapour and nitrogen, measured at N.T.P. The total heat of reaction will be 3150 gram/calories. This will be sufficient to raise the temperature of the products to 3620° C., if we assume that no heat is lost during the reaction.

In this case, therefore, the total volume that will be occupied by the reaction products at constant pressure will be

$$\frac{3.71 \times 3620}{273} = 49.2 \text{ litres.}$$

Therefore, the maximum pressure that can be produced will be

$$\frac{49.2}{3.71} = 13.2 \text{ atmospheres.}$$

These pressures are necessarily very much greater than those that are obtained experimentally, because (a) a considerable proportion of the heat that is generated by the reaction is lost by radiation and conduction and (b) the reaction will be arrested

or retarded before it is complete by the accumulation of the reaction products.

Owing to the necessarily somewhat slower reaction velocity of the dust explosion, there will be a greater loss of heat by radiation, but, even when this allowance is made, it will be seen that the maximum pressure that can be developed by the dust explosion is of the same order as that which is produced by the explosion of a gas mixture.

Owing to the slower rate of combustion of dust particles, when compared with gas molecules, the flame velocity tends to be lower.

Reference.

"Dictionary of Applied Chemistry" (Thorpe). Two articles: (a) "Explosion, Gaseous," by W. A. Bone and R. V. Wheeler; (b) "Flame," by A. Smithells.

CHAPTER V

THE INVESTIGATION OF EXPLOSIVE DUSTS

In 1911, a succession of serious factory explosions in this country drew attention to the explosive character of the clouds of dust that are produced in certain industrial processes. This led to a systematic investigation being made into the inflammability of these factory dusts.

Dr. R. V. Wheeler, who was in charge of the Mines Experimental Station at Altofts Colliery, examined over sixty kinds of dust that are produced in various mills and factories. With each dust, he determined (a) the relative ignition temperature—*i.e.*, the lowest temperature at which the dust readily inflames—thus distinguishing between harmless and dangerous dusts, and (b) the minimum temperature at which the more dangerous dusts could be ignited, from which the possibility of ignition being brought about by such common causes as electric sparks, heated metal, or a match flame could be inferred.

(a) THE RELATIVE IGNITION TEMPERATURE

This was determined by blowing a cloud of dust against a coil of platinum wire, the temperature of which could be measured and easily controlled.

In a horizontal glass cylinder, 8 cms. in diameter and 140 cms. long, and open at both ends, was supported a platinum coil of 32-gauge wire, closely wound on a thin-walled capillary tube of quartz; the temperature of the coil was registered by a thermocouple passing through the bore of the quartz tube. The dust to be tested was placed in

an even layer along a glass tube, of 2·5 cms. bore and 45 cms. long. This tube was supported just inside the glass cylinder, so that its open end was about 30 cms. from the heated platinum coil; the other end was connected by a tap with an arrangement for giving a constant puff of air.

In making an experiment, the platinum coil is heated to a suitable temperature—determined by preliminary trials—and a uniform dust cloud is produced in the glass cylinder by suddenly opening the tap. If ignition occurs, the temperature of the platinum coil is lowered ten or twenty degrees centigrade, and the experiment is repeated. Ultimately, two temperatures are obtained, differing by ten degrees centigrade, at one of which the dust ignites readily, while, at the other, ignition does not occur. The mean of these two temperatures is then taken to be the ignition temperature of the dust under the conditions of the test. When ignition occurs, the flame is calculated, both with and against the direction of travel of the dust cloud. In some cases, it issues from the open end of the cylinder, while in other cases it only travels 50 or 60 cms. away from the igniting coil. Some dusts, generally those containing a high percentage of mineral matter, only undergo ignition in the neighbourhood of the igniting coil, and no true propagation of flame takes place.

All the dusts were dried for an hour at 107° C., and, as far as possible, they were obtained with the same degree of fineness by passing them through a sieve of 200 meshes to the inch. In some cases owing to the fluffy nature of the substance, it could

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TABLE XIV.—Temperature of Ignition of Various Dusts When Small Portions of Cloud are Instantaneously Heated.

Substance.	Percentage of sample as received that passed a 200-mesh sieve.	Ignition-temperature. ° C.	Remarks.
Sugar	50	805	Flame travelled very rapidly in the cloud.
Dextrin (calcined farina)	Practically all passed through.	940	
Oil cake . . .	30	945	
Compound cake .	10	955	Flame travelled rapidly.
Starch	100	900	Flame propagated rapidly.
Sawdust . . .	20	970	Flame propagated rapidly.
Cocon	100	970	
Rice meal and sugar refuse	Fluffy; could not sieve.	970	Cloud formed easily, and flame travelled rapidly in it.
Cork	Practically all passed through.	975	Flame travelled rapidly.
Unextracted soya bean	10	975	—
Offal grinding (bran)	75	980	—
Wood flour . .	Fluffy; could not sieve.	985	Cloud formed easily, although the sample was unsieved.
Cork	50	900	Flame propagated rapidly
Malt	50	900	
Oat husk . . .	90	990	
Grain (flour mill)	50	995	—
Malze	70	1010	—
Tea	50	1010	—
Copal gum . .	70	1010	Flame propagated rapidly.
Starch	80	1035	—
Rape seed . .	Did not sieve; sample too small.	1050	Ignition-temperature probably lower, but no more dust available.
Leather (grain storage)	30	1050	—
Mustard . . .	20	1050	—
Flour	50	1050	—
Cornflour . . .	90	1060	—
Alfalfa	90	1060	—
Alfalfa	80	1070	—
Cork	90	1080	—
Briquette . .	90	1090	—

EXPLOSIVE DUSTS

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TABLE XIV (continued).

Substance.	Percentage of sample as received that passed a 200-mesh sieve.	Ignition-temperature. ° C.	Remarks.	
Gramophone record	100	1100	—	
"Dead" cork	100	1100	—	
Castor oil meal	60	1100	—	
Extracted soya bean	60	1140	—	
Cotton seed	} Fluffy; could not sieve.	—	{ Difficult to form a cloud. Such pieces as came in contact with the coil showed but slight tendency to inflame.	
Cotton seed and soya bean				
Cotton seed				
Spice milling	50	—	{ A small flare appeared at the coil at 1000° and upwards, but no flame was propagated.	
Drug grinding	30			
Drug grinding	75			
Drug grinding	70			
Tobacco	75	—	{ No ignition. A few sparks appeared around the coil above 1100°.	
Tobacco	75			
Organic ammonia	10	—	{ A small flare appeared at coil, but there was no propagation of flame.	
Grist milling	30			
Rice milling	20	—	{ Small flare at coil, but no propagation of flame.	
Coconut oil milling	None passed through sieve.			
Horn meal	50	—	{ No ignition; a few sparks only.	
Shellac composition	100			
Charcoal	90			
Coal (foundry blacking)	70			
Bone meal	40	—	{ No ignition.	
Lamp black	Could not be sieved.			
Rape seed (Russian)	90			
Retort carbon	30			
Sack cleaning	Fluffy; could not sieve.	—		
Blacking	75			
Foundry blacking	100			
Brush carbon	100			
Stale coke	70	—	{ No ignition. Sample much too coarse to form a cloud.	
Plumbago	95			
Bone charcoal	100			
Mineral and Ivory black	100			
Grain cleaning	None passed through.	—	{ No cloud could be formed.	
Shoddy	Could not be sieved.	—	{ No cloud could be formed.	

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not be sieved; in other cases, the sample was too coarse for any of it to pass through a 200-mesh sieve. The ignition temperatures of these coarser dusts have no relative value, and the experiment only served to show whether or not the substance is dangerously inflammable.

The ignition temperatures that are obtained in this way are only relative and refer solely to the particular experimental conditions that are employed. Very different values would be obtained in most cases by varying the fineness and concentration of the dust, or the amount of mineral matter that it contains. The results that were obtained by this test for different dusts are given in Table XIV. The ignition temperature of most bituminous coal dusts, as determined with the same apparatus, approximates to 1000° C. It will be seen, therefore, that a number of the dusts examined, particularly sugar, are more inflammable than bituminous coal dust.

(b) THE MINIMUM TEMPERATURE OF IGNITION

This was determined by allowing a cloud of dust to fall through a small porcelain tube, heated to a definite temperature and containing a small roll of copper gauze.

A loosely rolled spiral of copper gauze, about 25 mm. internal diameter and 10 cms. long, was supported in a vertical porcelain tube. The porcelain tube was electrically heated to a definite temperature that was registered by means of a thermocouple. 0.2 Gram of the dust was introduced into the horizontal dust tube and, by means

of a constant puff of air, was projected downwards over the heated gauze. If the gauze was hot enough, it ignited the dust cloud and a flame appeared at the lower end of the porcelain tube.

TABLE XV.—Minimum Ignition Temperatures for Various Dusts when Cloud is Heated Instantaneously.

Substance.	Minimum ignition-temperature. ° C.	Percentage of incom-bustible matter.
Dextrin (calcined farina) .	540	4.2
Sugar	540	1.4
Grist milling	600	7.8
Malt	600	11.7
Shoddy	610	15.9
Wood flour	610	3.2
Cork	620	0.6
Compound cake	620	9.3
Oat husk	620	13.4
Cocoa	620	8.1
Cornflour	620	0.9
Starch	630	0.4
Cork	630	1.7
Rice meal and sugar refuse	630	8.1
Grain (grain storage)	630	10.5
Rice milling	630	4.2
Extracted soya bean	630	12.5
Unextracted soya bean	630	12.5
Grain (flour mill)	630	18.2
Sawdust	635	3.9
Starch	640	1.5
Coconut oil milling	640	5.8
Tea	640	8.3
Offal grinding (bran)	640	30.0
Maize	645	8.0
Flour	650	1.5
Rape seed	650	No dust for analysis.
Castor oil meal	655	23.1
Chicory	660	7.5
Oil cake	660	27.3
Horn meal	670	5.3
Mustard	680	5.1
Tobacco	680. Very small flame.	21.0

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TABLE XV (*continued*).

Substance.	Minimum ignition- temperature. ° C.	Percentage of incom- bustible matter.
Spice milling . . .	680. Very small flame.	29.9
Drug grinding . . .	680. " "	58.7
Cork . . .	690	2.5
Shoddy . . .	690	15.8
Drug grinding . . .	690. Very small flame.	8.8
Organic ammonia . . .	690. " "	12.5
Drug grinding . . .	690. " "	21.3
Bone meal . . .	700	48.0
Tobacco . . .	700. Very small flame.	31.6
" Dead " cork . . .	740	11.6
Leather . . .	740	14.3
Copal gum . . .	750	1.8
Gramophone record . . .	750. Small flame.	32.8
Charcoal . . .	760. " "	10.4
Shellac composition . . .	780. " "	61.4
Briquette . . .	800. " "	9.9
Foundry blacking . . .	810. " "	10.5
Coal (foundry blacking) . . .	830. " "	21.4
Rape seed (Russian) . . .	A few sparks only, obtained at tem- peratures above 640° C.	72.8
Grain cleaning . . .	Not tested; dust much-too coarse.	8.9
Cotton seed . . .	No cloud could be formed.	7.4
Cotton seed . . .	" "	26.3
Cotton seed and soya bean . . .	" "	60.5
Lamp black . . .	No ignition could be obtained.	—
Retort carbon . . .	" "	4.4
Brush carbon . . .	" "	15.2
Mineral and ivory black . . .	" "	23.5
Mineral and ivory black . . .	" "	32.0
Stale coke . . .	" "	39.7
Blacking . . .	" "	60.4
Sack cleaning . . .	" "	74.6
Bone charcoal . . .	" "	77.0
Plumbago . . .	" "	78.2

Preliminary experiments showed that the more slowly the dust passed over the gauze—*i.e.*, the longer the time of contact—the lower was the temperature at which ignition could take place. These minimum ignition temperatures are given in Table XV. Again, it is necessary to remember that the actual figures may be considerably modified by changes in the fineness or ash content of the dust.

As the result of these experiments, Wheeler divided the various dusts into three classes :—

Class I : Dusts which ignite and propagate flame readily, the source of heat required for ignition being comparatively small—*e.g.*, a lighted match.

Class II : Dusts which are readily ignited, and which, for the propagation of flame, require a source of heat of large size or high temperature—*e.g.*, an electric arc—or of long duration—*e.g.*, a flame of a Bunsen burner.

Class III : Dusts which do not appear to be capable of propagating flame under any conditions that are likely to obtain in a factory, either (a) because they do not readily form a cloud in air, (b) because they are generally contaminated with a large quantity of incombustible matter, or (c) because the material of which they are composed does not burn rapidly enough.

This classification is shown in Table XVI, together with Wheeler's comments upon the dusts of the different classes.

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TABLE XVI.

Class I.

Sugar.	Malt.	Cornflour.
Dextrin (calcined farina).	Oat husk.	Flour (flour mill).
Starch.	Grain (flour mill).	Chicory.
Cocoa.	Maize.	Briquette.
Rice meal and sugar refuse.	Tea.	Gramophone record.
Cork.	Compound cake.	Extracted soya bean.
Unextracted soya bean.	Distillery meal dust.	
Wood flour.	Grain (grain storage).	
	Rape seed.	

"The dusts in Class I are arranged (roughly) in order of their inflammability. In this class, sugar, dextrin, starch and cocoa (the sample of cocoa dust tested appeared to have had sugar mixed with it) are the most dangerous, sugar exceptionally so. Sugar ignites when projected as a cloud against a surface heated to below red heat, and, when ignition has taken place, the flame travels throughout the dust-cloud with great rapidity."

Class II.

Copal gum.	Castor oil meal.	Horn meal.
Leather.	Oil cake.	Mustard.
"Dead" cork.	Offal grinding (bran).	Shoddy.
Coconut oil milling.	Grist milling.	Shellac composition.
Rice milling.	Myrobalans.	
Sawdust.	Valonia nuts.	

"Of the dusts in Class II, the samples of shoddy, being of a fluffy nature, did not readily form a cloud in air, but they contained a sufficient quantity of fine material to render them dangerous when in bulk. The sample of shellac composition contained

over 60 per cent. of incombustible matter, but was inflammable; a reduction in the quantity of incombustible matter present would render it dangerous."

Class III.

Organic ammonia.	Rape seed	Foundry
Tobacco.	(Russian).	blacking.
Spice milling.	Blacking.	Brush carbon.
Bone meal.	Grain cleaning.	Stale coke.
Coal (foundry	Drug grinding.	Plumbago.
blacking).	Cotton seed.	Bone charcoal.
Lamp black.	Cotton seed and	Mineral and
Sack cleaning.	soya bean.	ivory black.
Retort carbon.	Charcoal	

"Of Class III, the first ten are all more or less readily inflammable, but they showed no signs of being capable of *propagating* flame. It is possible, however, that other samples of the same materials, less contaminated with incombustible matter, or in a finer state of division, might be found capable of propagating flame. The classification of these dusts as harmless refers, therefore, to the particular samples tested only. The remaining dusts in Class III can be definitely regarded as harmless materials."

A modification of Wheeler's method has been developed by the United States Bureau of Mines. It has been used extensively with coal and many other dusts, and gives results that are said to agree consistently with those that are obtained with a large quantity of dust, when fired in a large-scale experimental mine gallery.

The apparatus is shown diagrammatically in Fig. 3. A glass explosion chamber, A, of 1400-c.c.

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capacity is fitted with a funnel-shaped glass dust-injector, B, and an igniting tube, C. The dust-injector is so arranged that a weighed amount of dust can be raised in a cloud by means of a carefully controlled puff

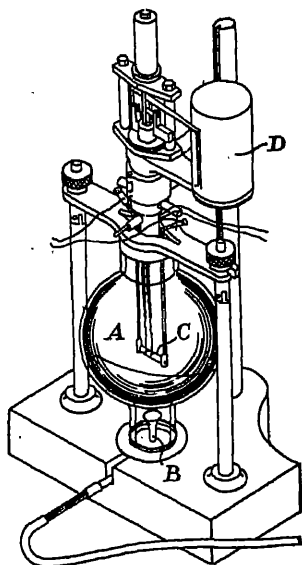


FIG. 3.—APPARATUS FOR DETERMINING THE INFLAMMABILITY OF EXPLOSIVE DUSTS.

of oxygen. The igniting tube, C, consists of a tube of a refractory material, on which is wound a heating coil of 14.2 mm. of platinum wire, forty turns to the inch. This is enclosed in a platinum tube made of 0.1 mm. sheet platinum, the wire being insulated from the platinum tube by a layer of alundum cement which is baked on. The temperature of the platinum tube is measured by means of a thermocouple; the pressure developed

by the explosion is recorded by a steam-engine indicator, D.

In carrying out an experiment, a weighed quantity of the dust is poured into the glass injector, B, and is tapped into position in the funnel stem. The coil is heated to the desired temperature and maintained at that temperature

for four minutes. Usually, 100 mgms. of dust is used in an experiment, the pressure of oxygen used to eject the dust being 15 cms. of mercury. With dusts of low inflammability, 300 mgms. is used, the pressure of oxygen required being 20 cms. Unless otherwise stated, the tests recorded are made with 200-mesh, air-dried samples. The dust is projected into the explosion globe and is ignited by contact with the igniting element. The pressure shown by the indicator is corrected for the increase due to the injected oxygen by deducting the pressure that is observed when no dust is used. The pressure recorded is always the average of at least three determinations. The pressures developed vary from a fraction of one pound with anthracite, or with dust of high ash content, to twenty pounds with sub-bituminous coals. Different determinations with the same sample of dust agree within 0.2 lb. for dusts that develop 10 to 15 lbs. pressure. Generally speaking, the relative inflammabilities of various dusts, as indicated by the pressure that is developed when they are exploded by this apparatus, confirm Wheeler's classification.

More recently, this apparatus has been employed by Trostel and Frevert in the modified form shown in Fig. 4. The dust is contained in a small cup, and is raised by a jet of air directed vertically downward. Interchangeable electrodes are introduced through the sides of the bomb, so that the dust can be ignited by electric arcs or high-tension sparks. In comparing the explosibility of different dusts, when ignited with different

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sources of ignition, Trostel and Frevert took into consideration (in addition to the explosion pressure) the character of the flame that was produced.

It will be shown later that the rate of combustion

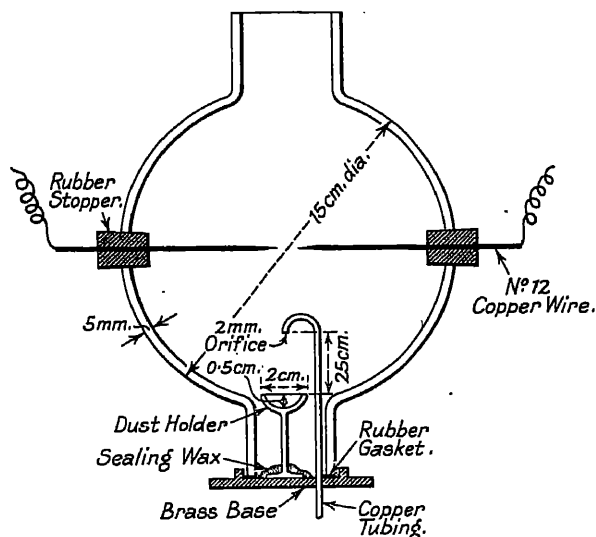


FIG. 4.—MODIFIED ARRANGEMENT OF EXPLOSION BOMB.

of a given dust, and, therefore, the maximum explosion pressure that is developed, may be greatly modified by varying such factors as the temperature of ignition, the ash and moisture contents of the dust, and the fineness of division and concentration of the dust in the dust-air mixture.

LARGER-SCALE LABORATORY TESTS

It is reasonable to assume that the special conditions that are likely to occur in a factory or mine can be more closely represented by tests that are carried out on a larger scale. The velocity and violence of an explosion develop as it travels away from the point of ignition; also, on a larger scale, secondary reactions may exert a greater influence upon the final result than in a small-scale experiment. Further, the distribution of dust in a large volume of air will be more irregular, producing a wider range of concentration than in a small volume.

The United States Bureau of Mines worked with a small, horizontal, experimental gallery, constructed of wood, and measuring 14 feet in length and 6 inches square inside. The gallery was closed at one end, and observation windows were placed at intervals along one side of it. The dust was injected into the gallery simultaneously through fourteen holes, spaced one foot apart along the bottom of the gallery. In this way, a uniform dust cloud was formed through the gallery. It was ignited by firing a small amount of black powder at the closed end. The length of the flame was determined by observation, and by noting how many pieces of guncotton, placed at intervals of a foot along the roof and floor of the gallery, had been burnt.

With this apparatus, it was found that some dusts—for example, alfalfa and flax—that were too coarse to be tested in the laboratory apparatus,

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ignited readily. A sample of potato starch, that failed to ignite in the small apparatus, exploded vigorously in this gallery. The most violent explosions were obtained with sulphur dust. Even when mixed with four times its weight of inert shale dust, it propagated flame as far along the gallery as did the standard bituminous coal (Pittsburg).

The gallery possessed the serious disadvantage that the dust settled quickly, so that the concentration rapidly changed during the interval of from one to three seconds that elapsed between the raising of the dust and its ignition. Results obtained with mixtures of dusts such as coal, flour or starch, with varying amounts of shale dust, were not concordant. Apparently, the shale dust settled more quickly than the lighter dust, so that the quenching effect of the shale dust in a given mixture became progressively smaller, the longer the time interval between the raising and the igniting of the dust.

It was thought that conditions more closely similar to factory conditions could be obtained in a vertical gallery. In this case, the dust would take some time to settle, and, if too concentrated at first, it would gradually pass through the explosive range of concentration as it settled. A vertical gallery, 10 feet high and 6 inches square inside, similar in design to the horizontal gallery, was constructed. The dust cloud was formed in the same way, but was ignited by an arc or an open flame—sources of ignition that are more likely to be present in factories and mills. More concordant

results were obtained with this apparatus—probably because the *average* composition of the cloud was more constant. A given dust showed well-marked variations, both in the ease of ignition and in the violence of the resulting explosion, according to the character of the source of ignition that was employed. The quenching effect of inert dust, also, was clearly shown.

EXPERIMENTAL MINES

Numerous large-scale experiments have been conducted in various countries in experimental galleries, constructed of steel or reinforced concrete, and similar in dimensions to the working galleries of a coal mine. These are used chiefly to determine the contributory causes and the mechanism of dust explosions.

At Eskmeals in Cumberland, such a gallery, 750 feet in length and 7 feet 6 inches in diameter, has been constructed of old Lancashire boiler shells. The general arrangement of the gallery is shown in Fig. 5 and in the frontispiece. One end of the gallery is open; the other is blanked off and is connected by a short, right-angled gallery 6 feet in diameter, with a ventilating fan. A valve is fitted at the junction of the fan gallery with the main gallery. By removing the blank which is normally used to close the end, the gallery can be made open at both ends. From the main gallery there branches, as shown, a smaller gallery 3 feet in diameter and 350 feet long. Suitable instruments are installed for recording the pressure developed by the explosion, the velocity with which

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this pressure is developed, the temperature and velocity of the flame, and the composition of the resulting gases. The pressure recorder is capable of measuring accurately pressures ranging from 1 lb. to 250 lbs.

To obtain an explosion, coal dust is distributed on the floor, and on narrow wooden ledges running horizontally along the sides of the

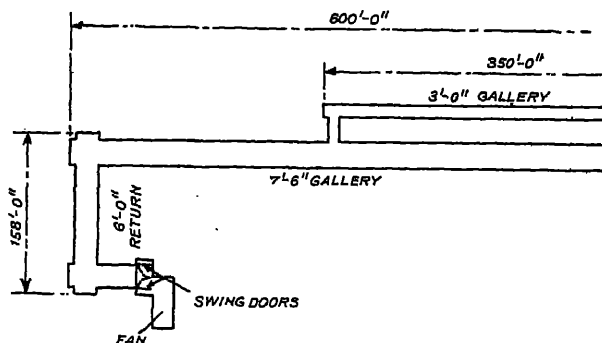


FIG. 5.—PLAN SHOWING ARRANGEMENT OF MINES EXPERIMENTAL STATION AT ESKMEALS.

gallery. Five 5-inch ledges are supported nine inches apart on each wall of the gallery, the lowest being 28 inches from the floor. The coal dust is distributed as uniformly as possible for a distance of 350 feet from the open end of the gallery, and at the rate of about 1 lb. of dust per foot run of gallery, corresponding to 0.4 oz. per cubic foot of air space. It forms a layer less than one sixty-fourth of an inch thick on the ledges, with, perhaps, rather a thicker accumulation on the floor. At the

inner end of the 350 feet length of gallery that has been treated with coal dust is placed a 10 feet length of steel tubing 3 inches in diameter, open at the ends, and loaded with coal dust at the rate of 2 lbs. per linear foot. Dust is also laid as a train 1 foot wide and 12 feet long upon planks laid on the floor of the gallery at the outer end of the 10-feet tube.

A cannon of wrought iron with a bore hole 2 feet 9 inches long by 2 inches diameter, charged with 24 ozs. of gunpowder lightly stemmed with 8 inches of moist clay, rests on the floor of the gallery with its muzzle pointing through the 10-feet tube towards the open end of the gallery. When the cannon is fired (electrically), a dense cloud of burning dust is projected from the outer end of the 10-feet tube, of sufficient volume to occupy the whole cross-section of the 7 feet 6 inches gallery.

Owing to the concussion and the movement of the resulting cloud of burning dust, the dust on the ledges and floor of the gallery is progressively raised into suspension and ignited throughout the entire length (350 feet) of the dust-treated gallery. Under suitable conditions, explosion occurs with extreme violence. A red flame of burning dust leaps from the open end of the gallery to a distance of up to 200 feet, followed by a dense cloud of smoke, through which pit props and other baffles are projected for distances of over a quarter of a mile.

By means of five special recording pressure gauges placed at distances of 50, 100, 150, 200 and

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250 feet, respectively, from the open end of the gallery, it is possible to follow the progress and development of the explosion. The curves in Fig. 6 record the change of pressure (lbs. per square inch) with time (in one-hundredths of a second) at each point of observation during an explosion that occurred when the dust was distributed along the gallery for a distance of 500 feet from the open end. From an examination of the curves, we see that, at 20·8-hundredths of a second after ignition, a rise of pressure is indicated by No. 1 gauge. This is due to the concussion wave that is sent out by the firing of the shot. It reaches No. 5 gauge, 200 feet distant, in 16·4-hundredths of a second, travelling, therefore, at the rate of 1200 feet per second. The effect of the concussion wave persists for 81-hundredths of a second, so that the pressure effect due to the coal dust explosion itself must be regarded as occurring to the right of the line AB. The greatest pressure is indicated by gauge No. 5, and it will be noticed that the rate of rise of pressure is considerably accelerated at this point, the pressure rising through 6 lbs. during 0·006 second. This sudden acceleration indicates that, after 1·05 second, the first stage of development of the explosion was almost complete, and, had the gallery been longer, a detonation wave would have been set up.

It will be noticed that the maximum pressure was reached at gauge No. 5 before it was at gauge No. 1, so that the time at which maximum pressure is produced at any point does not correspond to the passage of flame at that point. It is clear

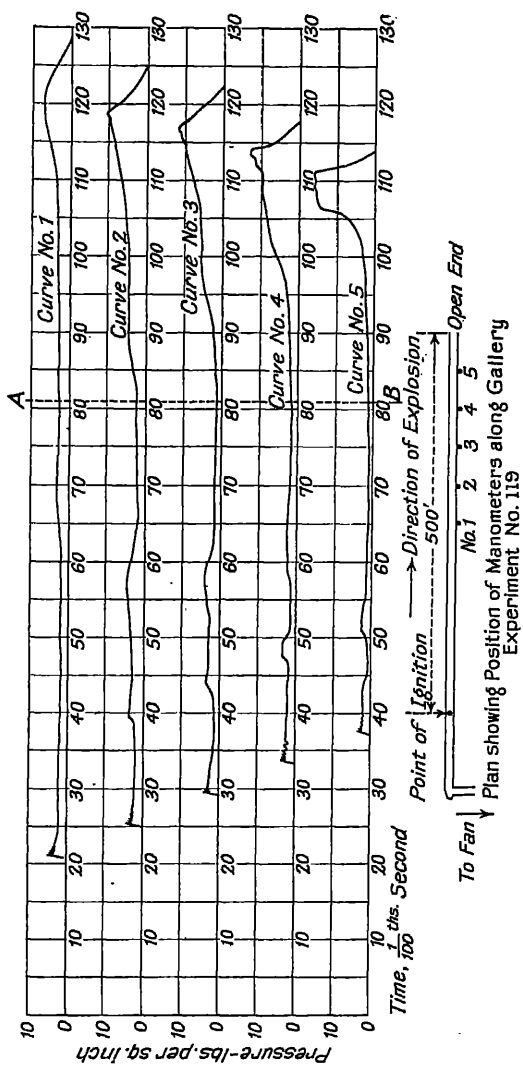


FIG. 6.—PRESSURE-TIME CURVES.

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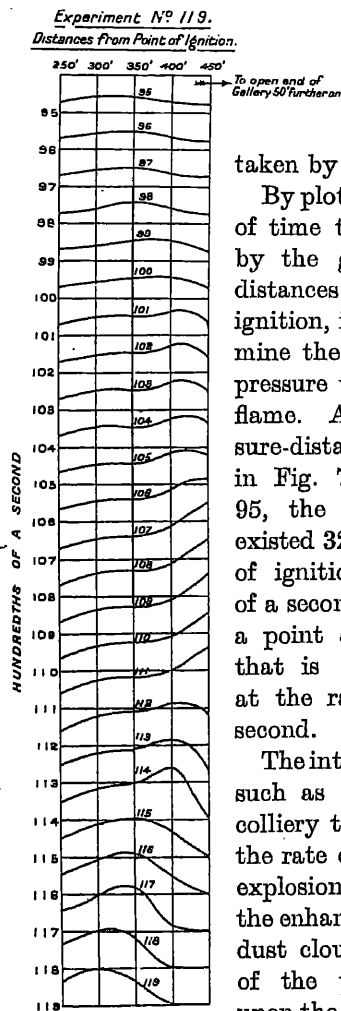


FIG. 7.—PRESSURE-DISTANCE CURVES.

that a wave of pressure travels towards the point of ignition—i.e., in a direction contrary to that

taken by the flame.

By plotting for each interval of time the pressure recorded by the gauges against their distances from the point of ignition, it is possible to determine the velocity of the first pressure wave—that is, of the flame. A series of these pressure-distance curves is shown in Fig. 7. At time interval 95, the crest of the wave existed 325 feet from the point of ignition. Five-hundredths of a second later, it existed at a point 50 feet further on—that is to say, it travelled at the rate of 1000 feet per second.

The introduction of obstacles such as props and bars and colliery tubs greatly increases the rate of development of an explosion, probably because of the enhanced turbulence of the dust cloud and the reflection of the pressure wave back upon the burning gas.

An elaborate series of experiments, extending over a period of sixteen years, has been carried out in this country at the experimental gallery at Altofts (from 1908 to 1911), and, subsequently, at Eskmeals. The work is described in the reports to the Home Office of the Explosions in Mines Committee, and in the reports of the Safety in Mines Research Board. These reports deal with the relative inflammability of coal dusts, the effect of an admixture of an incombustible dust with the coal dust, the possibility of incombustible dusts promoting the ignition of otherwise unflammable mixtures of firedamp and air, the lower limits of combustion of mixtures of methane and air, the effect of different dusts upon the health of the workers, and the general conditions that are necessary for the production of a coal dust explosion and the means that can be taken to prevent it.

Similar experimental galleries, in which, as far as possible, the practical working conditions, as obtained in a coal-mine, are represented, have, with slight modifications, been erected in the United States of America, France, Austria, Belgium and Germany.

References.

"Dust Explosions," by D. J. Price, H. H. Brown, H. R. Brown and H. E. Roethe. (National Fire Protection Association, Boston, Mass., 1922).

(This book deals very fully with the subject of dust explosions, and contains much valuable information which has been freely drawn upon in this chapter, and in chapters VI and VII.)

"Coal Dust Explosions, Eskmeals," by R. V. Wheeler. (H.M. Stationery Office, 1924.)

CHAPTER VI

DUST EXPLOSIONS

THE most characteristic property of any explosion, whether of gas or dust, is the rapid, practically instantaneous production of a sudden increase of pressure. This may be due to the production of an increased volume of gas which may burst the containing vessel, or it may be due to the impact of a wave of compression that travels through the gas with a velocity equal to, or greater than that of sound. If combustion occurs so slowly that the heat of reaction is dissipated as quickly as it is produced, there is comparatively little increase of pressure. Clearly, the more rapidly combustion is accomplished, the higher will be the maximum expansion pressure that is produced by the reaction. We may, therefore, regard the maximum pressure that is produced by explosion as a measure of the inflammability of a given dust under varying experimental conditions. Only in favourable circumstances will explosion result in the formation of a detonation wave.

THE EXPLOSION PRESSURE

The "expansion pressure" that is developed is due either to the rapid formation of gaseous reaction products, or to the expansion of the air by the heat of the reaction. The pressure that is produced by an explosion of starch dust is mainly due to the rapid formation of relatively large volumes of gases. Sulphur, on account of its low ignition temperature, explodes more readily than starch, but, since it produces only half the volume

of gas that an equal weight of starch produces, it explodes with correspondingly less violence. With some dusts—*e.g.*, aluminium—that do not produce any gas, but, on the contrary, use up oxygen from the air, the explosion pressure is due entirely to the thermal expansion of air. The heat of reaction of aluminium dust is so great that the explosion pressure is of the same order as that which is produced by starch.

Since, in most cases, the disastrous consequences of a factory explosion are mainly due to the expansion pressure that is developed, a measurement of the expansion pressures that are developed by different substances under standard conditions provides a satisfactory empirical basis for a comparison of the explosion hazard of each dust. It affords a method of comparing the inflammability of different concentrations of the same dust. It does not afford a true basis of comparison for the relative inflammability of different materials, since, in one case, the explosion may be produced entirely by thermal expansion, in another case, by gas production, and in others by both. The best estimate of relative inflammability is obtained from a consideration of the lowest limits of concentration and ignition temperature at which the dust can propagate flame freely.

When the composition of the dust cloud is such that combustion occurs rapidly enough to produce a detonation wave, the resulting "detonation pressure" that is produced by the impact of this high velocity compression wave is not only very much greater than the corresponding expansion

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pressure, but differs from it in exerting a shattering effect upon any obstacle which it encounters. This shattering effect is probably due to the regular distribution of the impact over the surface of the obstacle, the effect being equivalent to that of a very large number of impacts delivered simultaneously at all points of the surface. Detonation waves are probably formed during the progress of a coal dust explosion along the galleries of a mine.

The pressure that is developed by the explosion of a given dust is profoundly modified by the following factors :—

- (1) The concentration of dust employed.
- (2) The physical condition of the dust.
- (3) The chemical composition of the dust.
- (4) The composition of the atmosphere.
- (5) The temperature, extent and duration of ignition.

(1) THE CONCENTRATION OF THE DUST

The particles of a dust cloud, although many thousand times as large as the molecules of a gas, are yet exceedingly small; consequently, the dusty material is in intimate contact with the gas in which it is dispersed. It is reasonable to expect, therefore, that a dust cloud will burn with maximum velocity when the concentration of the actual combustible is chemically equivalent to the concentration of oxygen in the gas, for, in such circumstances, the number of molecules of combustible that are in direct contact with molecules of oxygen is a maximum. This is found to be

the case. The explosion pressure is a maximum at this concentration, and diminishes rapidly as the concentration departs from this value in either direction.

The relation between the concentration of lycopodium dust and the explosion pressure is shown in Table XVII.

TABLE XVII.—Relation between Concentration of Lycopodium Dust and Inflammability of Cloud.

Concentration of dust, grams per 100 c.c.	Pressure, lbs. per sq. in.
0.2	33
0.3	52
0.5	60
1.0	33
1.5	19
3.5	9
5.0	7

Beyond a lower and upper limit of concentration, the dust cloud is not inflammable. Evidently, the presence of an excess of either constituent serves but to dilute the other constituent, and so retard the reaction.

The lower limit of concentration for a number of industrial dusts has been determined by Trostel and Frevert, by the method described in Chapter V. The chemical composition and the physical properties of these dusts are shown in Table XVIII.

The explosion pressure was determined repeatedly, using diminishing concentrations of dust, until a concentration was reached at which flame and pressure were no longer produced. The character of the flame was noted, and the pressure was automatically recorded on a smoked paper.

TABLE XVIII.—Composition and Properties of Dusts used in Tests.

Dust.	Chemical composition.				Physical properties.				
	Non-combustible.		Combustible.		Ignition temperature.*	Heat of combustion.†	Relative inflammability.‡	Through 200-mesh screen.	
	Moisture.	Ash.	Starch.	Protein.				Lbs. per sq. in.	%
Corn starch	%	%	%	%	° C.	per gm.			
Wheat elevator	11.10	0.12	88.26	0.52	640	4.188	18.7	100	100
Corn elevator	9.20	18.17	34.83	12.54	700	4.188	12.2	89	100
Sulphur	7.84	13.41	67.41	6.55	625	3.007	12.2	89	100
Crystalline, 68-80%	0.05	0.36	—	—	280	2,120	10.2	74	100
Amorphous, 80-76%	—	—	—	—	—	—	—	—	—
Sugar	0.04	0.01	—	—	650	3,955	11.4	83	100
Pure sugar, 99%.	—	—	—	—	—	—	—	—	—
Foreign organic material, 0.95%.	—	—	—	—	—	—	—	—	—
Aluminium	0.27	—	—	—	925	7,244	13.4	99	100
Fe, Si, Cu, Pb, Mn = 95.20%.	—	—	—	—	—	—	—	—	—
Organic matter = 3.83%.	—	—	—	—	—	—	—	—	—
Standard Pittsburg coal	1.85	7.04	—	—	900	7,848	8.7	64	87.2
Volatile matter, 36.43%.	—	—	—	—	—	—	—	—	—
Fixed carbon, 54.06%.	—	—	—	—	—	—	—	—	—

* Determined by glow-ignition in bomb.

† Commonly accepted values (moisture-free substances).

‡ Referred to corn starch as 100% on basis of lbs. per sq. in. pressure in bomb.

§ Determined by the U.S. Bureau of Mines at the Pittsburg Station.

|| Determined by the U.S. Bureau of Standards.

A number of different determinations were made with each concentration of dust. Variations of chemical composition and particle size were eliminated as far as possible by using a uniform sample, carefully analysed, moisture-free, and screened to the same maximum size. All other experimental conditions, such as the temperature and the duration of ignition, were also kept constant. Each set of experiments was repeated three times, using different methods of ignition—namely, a platinum wire glower, a high-amperage arc, and a high-voltage induction coil spark. The results of these experiments are collected in Table XIX.

In determining the lowest concentration at which explosion occurred, that concentration was taken at which good propagation, accompanied by a positive pressure, was obtained in at least 50 % of the total trials made. Ignition may occur locally at lower concentrations, and may wander fitfully through the dust cloud like an *ignis fatuus*, but without producing any of the characteristics of explosive combustion. Such poor mixtures are regarded as non-explosive.

It is important to note the effect of the temperature and duration of the source of ignition upon the inflammability of the dust. This is more readily to be seen in Table XXIII, in which the lower limits of concentration are compared for the various materials. In every case, the dust ignites at a lower concentration—that is, more readily—when it is heated by the glower. This is because the greater heat capacity of the glower

TABLE XIX.—Results of Tests with Spherical Glass Bomb.

Type.	Dust.		Glowler ignition at 1200° C.			Arc ignition at 33 v., 5 amps.			Induction coil spark ignition at 6.5 volts, 3 amps.		
	Weight used.		Average pressure generated.			Average pressure generated.			Average pressure generated.		
	Total.	Per litre.	Flame characteristics.	Flame characteristics.	Lbs. per sq. in.	Flame characteristics.	Flame characteristics.	Lbs. per sq. in.	Flame characteristics.	Flame characteristics.	Lbs. per sq. in.
Powdered corn starch.	Mgms.	Mgms.									
	75	51.0	Good propagation.	Good propagation.	13.7	Good propagation.	Good propagation.	14.0	Good propagation 7 times.	Good propagation 7 times.	13.7
	25	17.2	" "	" "	7.2	" "	" "	6.7	Good propagation 8 times.	Good propagation 8 times.	4.0
	20	13.7	" "	" "	5.3	" "	" "	4.5	Good propagation.	Good propagation.	3.4
	15	10.3	" "	" "	3.2	" "	" "	2.3	Positive flame.	Positive flame.	1.8
	10	7.0	" "	" "	2.1	Positive flame.	Positive flame.	1.0	" "	" "	0.7
	7	4.9	No flame twice. Flicker twice.	No flame twice. Flicker twice.	0.3	" "	" "	0.4	Positive flame 3 times. Flicker 4 times.	Positive flame 3 times. Flicker 4 times.	0.5
	5	3.4	Positive flame once. Flicker twice.	Positive flame once. Flicker twice.	0.4	No effect.	No effect.	0.0	Flicker 5 times.	Flicker 5 times.	0.0
	3	2.0	Flicker once. No flame 4 times.	Flicker once. No flame 4 times.	0.2						
	75	51.0	Good propagation.	Good propagation.	12.2	Good propagation.	Good propagation.	10.1	Good propagation 4 times.	Good propagation 4 times.	13.3
Corn elevator dust.	25	17.2	" "	" "	5.5	" "	" "	5.1	Good propagation.	Good propagation.	2.6
	20	13.7	" "	" "	4.4	" "	" "	4.7	Good propagation twice.	Good propagation twice.	2.3
	15	10.3	" "	" "	3.2	" "	" "	3.0	Positive flame.	Positive flame.	1.0
	10	7.0	Positive flame 6 times.	Positive flame 6 times.	0.3	Positive flame.	Positive flame.	1.0	" "	" "	0.0
	7	4.9	Positive flame twice. Flicker once.	Positive flame twice. Flicker once.	0.1	No effect.	No effect.	0.4	No effect.	No effect.	0.0
	5	3.4			0.0			0.0			0.0

TABLE XIX (continued)

Type.	Dust.		Glowor ignition at 1200° C.			Are ignition at 33 v., 5 amps.			Induction coil spark ignition at 0.5 volts, 3 amps.	
	Weight used.		Flame characteristics.	Average pressure generated. Lbs. per sq. in.	Flame characteristics.	Average pressure generated. Lbs. per sq. in.	Flame characteristics.	Average pressure generated. Lbs. per sq. in.	Flame characteristics.	Average pressure generated. Lbs. per sq. in.
	Total. litre.	Per Mgrs.								
Standard Pittsburg coal.	75	51.0	Good propagation.	8.7	Good propagation.	4.0	No effect found in a total of 9 trials, 3 each using:	No effect found in a total of 9 trials, 3 each using: 75 mgrs. dust. 150 mgrs. dust. 500 mgrs. dust.		
	50	34.4	"	6.1	Good propagation 3 times. Positive flame once.	1.9				
	35	24.1	—	—	Good propagation twice. Positive flame once.	1.3				
	30	20.1	Good propagation.	2.5	Good propagation 3 times. Positive flame twice.	1.0				
	25	17.2	Good propagation 3 times. Positive flame twice.	1.7	Good propagation 4 times. Positive flame 4 times.	0.5				
	20	13.7	Positive flame.	1.1	Good propagation twice. Positive flame twice.	0.5				
	15	10.3	"	0.8	No effect once. Positive flame twice.	0.4				
	10	7.0	"	0.5	No effect twice. No effect once. Flicker twice.	0.1				
Powdered sugar.	7	4.9	Flicker.	0.2	No effect twice. Good propagation.	0.3		Good propagation twice. Good propagation 3 times. Flicker once.	11.3 7.1 2.5 0.0	
	5	3.4	"	0.1	"	9.7				
	75	51.0	Good propagation.	11.4	"	7.3				
	50	34.4	—	—	"	—				
	35	24.1	Good propagation.	—	"	0.1				
	25	17.2	—	5.0	"	3.7				

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TABLE XIX (continued)

Type.	Dust.		Glowar Ignition at 1200° C.			Arc Ignition at 33 v., 5 amps.			Induction coil spark Ignition at 6.5 volts, 3 amps.		
	Weight used.		Flame characteristics.	Average pressure generated.		Flame characteristics.	Average pressure generated.		Flame characteristics.	Average pressure generated.	
	Total.	Per litre.		Lbs. per sq. in.			Lbs. per sq. in.			Lbs. per sq. in.	
Powdered sugar (cont.).	Mgms.	Mgms.									
	20	13.7	Good propagation.	4.3		Positive flame.	3.1				
	15	10.3	"	3.0		"	2.1				
	10	7.0	Positive flame.	2.2		Flicker.	1.3				
	7	4.9	"	1.2		Flicker once.	0.6				
	5	3.4	"	0.8		No effect.	0.1				
Powdered alum.	3	2.1	"	0.4							
	1.5	1.0	Flicker 3 times.	0.2							
	75	51.0	Good propagation.	13.5		Good propagation.	11.7		Good propagation.	16.7	
	50	34.4	"	5.7		"	10.0		"	12.0	
	35	24.1	Good propagation.	4.0		"	8.2		"	8.5	
	25	17.2	"	3.6		"	7.0		"	6.7	
	20	13.7	"	2.8		"	4.9		"	4.8	
	15	10.3	"	2.3		"	3.8		Positive flame.	2.6	
	10	7.0	Good propagation twice.	1.1		"	2.2		Flicker once.	0.0	
	7	4.9	Flicker twice.	0.7		Positive flame.	1.2				
Wheat elevator dust.	Good propagation once.		Flicker 4 times.	0.0		Flicker.	0.3				
	5	3.4	No effect.	0.0		Flicker 4 times.	0.0				
	3	2.1	"	—		No effect.	0.0		Positive flame once.		
	1.5	1.0	"	—		"	—		"		
	150	100.0	"	—		"	—		"		
	125	84.0	Good propagation.	12.2		Good propagation.	9.6		Not registered.	Not registered.	
	75	51.0	"	—		"	—		"	4.0	
	35	24.1	"	—		"	—		"	1.6	
									"	Not registered.	

TABLE XIX (continued)

Type.	Dust.		Glacier ignition at 1200° C.			Arc ignition at 33 v., 5 amps.			Induction coil spark ignition at 6.5 volts, 3 amps.		
	Weight used.		Flame characteristics.	Average pressure generated. Lbs. per sq. in.	Flame characteristics.	Average pressure generated. Lbs. per sq. in.	Flame characteristics.	Average pressure generated. Lbs. per sq. in.	Flame characteristics.	Average pressure generated. Lbs. per sq. in.	
	Total.	Per Mgm.									
Wheat elevator dust (cont.).	25	17.2	Good propagation.	5.2	Good propagation.	4.8					
	20	13.7	"	3.5	"	3.0					
	15	10.3	"	2.0	"	1.9					
	10	7.0	Positive flame twice.	0.6	Positive flame 3 times.	0.7					
	7	4.9	Flicker once.	0.2	Flicker 3 times.	0.1					
	5	3.4	"	0.0	Flicker (?) once.	0.0					
	3	2.0	—	—	Good propagation.	10.1	Good propagation.	0.3			
Powdered sulphur.	75	51.0	Good propagation.	10.3	Good propagation.	10.1	"	2.2			
	35	24.1	—	4.3	Good propagation.	4.6	"	1.4			
	25	17.2	Good propagation.	3.4	"	1.5	Positive flame 3 times.	0.7			
	20	13.7	"	2.2	Positive flame.	0.5	Positive flame 3 times.	0.4			
	15	10.3	"	1.3	"	0.2	Flicker twice.	0.4			
	10	7.0	"	1.0	"	0.1	Positive flame 5 times.	0.4			
	7	4.9	Positive flame.	1.0	Flicker.	0.1	Flicker once.	0.0			
	5	3.4	Flicker.	0.3	No effect.	0.0	Flicker once.	0.0			
	3	2.0	"	0.2	—	—	No effect.	0.0			

Good propagation: A large flame, extending from 5 cms. to the entire width of the bomb from the ignition source.
Positive flame: A short flame, clearly visible, extending a maximum of 4 cms. from the ignition source.
Flicker: A flash, just visible, at the ignition source.
No effect: Failure to ignite or explode.

enables it effectively to warm by radiation the surrounding air and dust, prior to ignition. Similarly, the dust is ignited more readily by the arc than by the spark.

From these results, it may reasonably be inferred that a dust cloud in a factory will be more readily ignited by an open fire or flame, and to a smaller extent by an electric arc than by an electric spark.

The Upper Limit of Concentration.—Comparatively few determinations have been made of the upper limit of concentration beyond which the dust cloud is no longer inflammable. Beyersdorfer finds that the upper limit for sugar dust is reached when the air contains 13.5 grams per litre.

(2) THE PHYSICAL CONDITION OF THE DUST

The inflammability of a given dust depends very much upon the size of the particles, their structure, the presence of adsorbed gas upon them, and the extent to which they are electrically charged.

Degree of Dispersion.—For a given concentration of any particular dust cloud, both the inflammability and the rate of combustion are increased by increasing the degree of dispersion. Not only is the total surface of the dust greater, so that it is more completely available, but the smaller particles are more readily raised to the ignition temperature by a given source of heat, and, being more numerous, are closer together, and, therefore, better able to communicate heat to one another. In most very fine dusts, also, there will be a

proportion of particles that are small enough to be in Brownian motion; these will facilitate the propagation of ignition through the cloud. The more finely-divided the dust is, the more clearly will the behaviour of the cloud approach to that of a gas mixture. In no case, however, has dust been observed to burn with a velocity comparable with that of a gas mixture, for even the finest dust particle will take a considerable time to become ignited and burn out, when compared with a gas molecule.

At the same time, it must be remembered that the complete combustion of such organic substances as starch and sugar results in the formation of relatively large volumes of gas, so that an explosion of starch or sugar dust may develop a maximum pressure that is as great as, or greater than, that produced by the explosion of a gas mixture.

TABLE XX.

Dust. Maximum size of particles mm.	Pressure, lbs. per sq. in.						
	0.02	0.025	0.03	0.04	0.05	0.06	0.11
Wood dust . . .	18.3	—	18.1	—	15.5	—	10.0
Oat and corn . . .	15.7	—	—	14.2	—	—	8.7
Potato starch . . .	14.6	—	14.0	—	12.8	—	11.1
Pittsburg coal . . .	—	—	12.6	—	10.3	—	3.0
Wheat flour . . .	—	14.0	—	13.0	—	12.5	9.6
Cocoa . . .	—	—	7.3	11.3	—	10.7	10.2

The pressures generated by various dusts, separated into fractions of different degrees of fineness, are compared in Table XX. In every case, the finer dust is more inflammable. In these experiments, however, none of the dust is particularly fine; very much greater explosion

pressures would probably be obtained with particles of 0.001 mm. diameter, corresponding to a mesh of 300 to the inch.

Structure of the Particles.—Little is known of the relation that exists between the inflammability of a given substance when in a finely-divided condition, and the structure of the particles—more particularly, the character of their surface. It has been observed repeatedly that finely-divided substances readily adsorb the gas in which they are disintegrated. There is no doubt that an open, micro-cellular surface will adsorb gas more readily than a relatively close-grained, smooth surface. This may explain the readiness with which pyrophoric iron or lead ignites spontaneously in air. Beyersdorfer considers that the combustion of sugar dust is assisted and accelerated by the adsorption of oxygen by the particles. When the particles possess an open structure, they will, in similar circumstances, burn more readily and more completely than particles that are more compact.

(3) CHEMICAL COMPOSITION OF THE DUST

Combustible substances differ widely in the readiness with which they take fire and burn. Rapid combustion may be due to a greater readiness to combine with oxygen (ease of oxidation), to the production, when heated, of a combustible gas or vapour (content of volatile matter), or to the formation of a gaseous or porous combustion product that does not interfere with the access of air to the unburnt portion of the combustible.

Sometimes, in the absence of a good draught, the products of combustion, even gaseous ones, may accumulate at the surface of the burning substance and, by restricting the access of oxygen, check combustion.

Ease of Oxidation.—The temperature at which any combustible substance can ignite in air necessarily depends upon, and is a measure of, the intensity of chemical attraction that exists between the substance and oxygen. This is a specific property, and varies widely for different substances. Sulphur ignites in air readily at 280°C. , and a cloud of sulphur dust, containing 7 mgms. per litre, allows ready propagation of flame from particle to particle, even though the heat of combustion of sulphur (2120 calories) is relatively small. On the other hand, bituminous coal dust, of which the temperature of ignition is about 900°C. , cannot propagate ignition unless there is at least 17.2 mgms. of dust per litre. Aluminium powder has a high ignition temperature (925°C.) and, also, a high calorific value. Owing to its high heat of combustion, and the production of a flame temperature of over 3000°C. , ignition can be propagated through a cloud of aluminium dust containing only 7 mgms. per litre.

Volatile Matter.—Many combustible substances that are met with in industry contain a proportion of matter that is volatile at temperatures below the ignition point of the substance itself. When the substance is heated—*e.g.*, by a suitable source of ignition—this volatile portion will be volatilised the more completely, the finer the particles. The

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gas or vapour that is produced may be combustible, in which case it will facilitate the ignition of the dust by becoming ignited itself at a lower temperature, and supplementing the heating effect of the original source of ignition. The ignition of bituminous coal dust or sugar dust probably takes place in two stages, the actual ignition of the dust being preceded by the distillation and ignition of combustible vapours and gases.

The influence of volatile matter is probably most pronounced in the case of coal, anthracite and semi-bituminous coals being markedly less inflammable than bituminous coals. There is no definite quantitative relationship between the inflammability of the coal and the content of volatile matter; apparently, the chemical composition of the volatile matter is also a determining factor. Wheeler found that the inflammability of different samples of coal was proportional to the amount of paraffins that was distilled from them.

In some cases, the volatile matter is incombustible, and will check the propagation of ignition by absorbing some heat—as latent heat of evaporation—and by diluting the oxygen in the immediate neighbourhood of the particle with an inert gas.

The products of decomposition by heat of cellulose and starch, and of a bituminous (Pittsburg) and semi-bituminous (Wyoming) coal, are compared in Table XXI. Cellulose and starch decompose by heat more readily than coal, but the gases and vapours that are produced during the early stages of decomposition are from 80 to 90 per cent. incombustible. It will be noticed that the

actual amount of combustible gases that are evolved by starch and cellulose is very much greater than that evolved by the coals. In the former case, however, the inflammable gas consists largely of carbon monoxide, which has a relatively low inflammability when compared with methane and other low hydrocarbons, which are the important constituents of the coal gas.

TABLE XXI.—Volatile Matter Produced by Complete Distillation of Cellulose and Starch to 500° C. and of Two Coals to 450° C.

	Dry material to 500° C.		Air-dried material to 450° C.	
	Cellulose.	Starch.	Pittsburg coal.	Wyoming coal.
Total volatile (per cent.) .	67.1	71.4	22.00	35.45
Water (per cent.) :				
Free	—	—	0.03	5.08
Combined	31.7	29.7	4.30	12.04
Acetic acid (per cent.) .	3.3	5.3	—	—
Aldehydes and ketones (per cent.)	5.0	6.8	—	—
Carbon dioxide (per cent. by weight)	11.3	13.1	0.31	3.78
Carbon monoxide (per cent. by weight)	4.8	7.6	0.21	1.00
Tar (per cent. by weight) .	3.3	2.7	12.70	8.17
Inflammable gases (other than CO)	1.3	2.0	3.10	2.80
Gas (as c.c. per 100 grams) :				
Carbon dioxide	6,303	7,365	174	2,128
Carbon monoxide	4,208	6,821	187	1,420
Unsaturated hydrocarbons .	213	347	352	394
Methane	1,056	1,273	1,053	1,778
Ethane, etc.	281	503	1,147	860
Hydrogen	247	370	653	1,120
Total gas	12,428	16,769	4,460	7,724
Inflammable gases, as per cent. (by volume) of total gases	48.8	56.1	96.1	72.6
Inflammable material, as per cent. (by weight) of total volatile	15.4	10.0	73.3	25.4

Any moisture that is associated with a dust may be regarded as a particular example of incom-

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bustible volatile matter. It absorbs heat in being warmed and evaporated, and so reduces the extent to which the dust itself is warmed by the source of ignition. The ignition temperature is raised and the propagation of flame made more difficult. This retarding effect is directly proportional to the amount of moisture that is present. By increasing the moisture content sufficiently, it is possible to render many dusts non-inflammable. Very rarely is the natural moisture content of a dust sufficient to prevent combustion, for, as a general rule, if the dust can form a cloud, it is dry enough to be inflammable. Also, when dispersed in the air, the dust will tend to dry rapidly, owing to its large specific surface.

Since the possibility of propagating ignition through a dust cloud depends upon successive particles of the dust being heated to a sufficiently high temperature, it is clear that the specific heat of the material will be an important factor. Organic materials, such as cellulose (0.37) and sugar (0.35), have relatively high specific heats, and, therefore, will absorb more heat for a given amount of temperature. The specific heats of inorganic substances, such as sulphur (0.18) and aluminium (0.25), are relatively low. In many industrial dusts, there is a proportion of incombustible material; this absorbs heat, and, after combustion is complete, remains as ash. A commonly accepted value for the specific heat of a siliceous ash is 0.25. In addition to an incombustible substance forming an integral part of the dust, the dust cloud may contain inert dust as a

separate constituent. If the amount of inert material present, whether combined or separate, is sufficient, it will absorb so much of the heat of combustion that the temperature of the combustible matter will not be raised to the ignition point. Under such conditions, the propagation of flame through the dust cloud will become impossible, the flame being quenched by the inert matter present in the cloud. Clearly, the extent to which inert matter can prevent ignition will depend upon the proportion of such inert matter that is present, and also upon its specific heat and that of the combustible portion. The distribution of heat between the combustible and incombustible constituents of wheat elevator dust may be calculated as follows. The dust may be assumed to contain 9 per cent. moisture, 19 per cent. ash and 72 per cent. combustible matter.

The combustible constituent of wheat elevator dust will begin to decompose at about 150° C. When 1 gram of this dust is heated from 20° C. to 150° C., heat will be absorbed by moisture, by ash constituents and by incombustible constituents, as follows :—

$$\begin{aligned} (a) \text{ The heat absorbed by 0.09 gram of moisture} \\ &= 0.09 (100 - 20) + 0.09 \times 537 + 0.09 (150 \\ &\quad - 100) \ 0.465 \\ &= 57.62 \text{ calories.} \end{aligned}$$

$$\begin{aligned} (b) \text{ The heat absorbed by 0.19 gram of ash} \\ &= 0.19 (150 - 20) \ 0.25 \\ &= 6.175 \text{ calories.} \end{aligned}$$

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Therefore, the total heat absorbed by incombustible constituents = 63.80 calories.

(c) The heat absorbed by the combustible constituents

$$\begin{aligned} &= 0.72 \times 0.35 (150 - 20) \\ &= 32.76 \text{ calories.} \end{aligned}$$

Therefore, the ratio of heat absorbed by the incombustible constituents to that absorbed by the combustible constituents is

$$\frac{63.80}{32.76} = 1.9.$$

In this case, evidently, 67 per cent. of the heat absorbed by the dust has been taken up by the moisture and the ash.

In Table XXII, the retarding influence of the incombustible portion of the dust is illustrated with various samples of rice dust. Although, for a given dust, an increase in the percentage of incombustible matter reduces the inflammability, yet the percentage of ash that can be present in an explosive dust varies within very wide limits: thus, rice dust may contain 57 per cent. of ash, and still be inflammable, while carbon dust may contain only 4 per cent. of ash and be incapable of ignition. Generally speaking, the more inert matter that a dust naturally contains, the higher will be the concentration necessary for the propagation of ignition. Thus, the lower limit of concentration for corn and wheat elevator dusts, containing, respectively, 13.41 and 18.17 per cent. of ash, is 10.3 mgms. per litre, whereas starch,

containing 0.12 per cent. of ash, will explode readily if 7 mgms. are present per litre of air.

TABLE XXII.—Effect of Ash on Inflammability of Rice Dusts.

Dust.	Explosion pressure, lbs. per sq. in.	Ash, per cent.
Rice polish dust from polisher	10.1	8.06
Rice polish dust from collector around polisher	9.3	7.05
Rice bran dust	8.7	21.49
Rice dust from cleaning	7.9	29.33
Rice dust	7.1	35.52
Rice dust from shaker	4.8	53.40
Rice dust from bins above cyclone from receiving aspirator	4.8	56.77
Rice dust from clippers	3.9	50.40
Cyclone dust from rough rice receiving aspirator	0.0	47.666

The deliberate addition of moisture or inert dust to a given combustible dust, in order to prevent combustion, is practised widely in certain dusty industries—notably, the coal-mining industry. This is discussed in detail when considering the prevention of coal-dust explosions.

(4) THE COMPOSITION OF THE ATMOSPHERE

The inflammability of a given dust is diminished when the percentage of oxygen in the air in which the dust is suspended is reduced. It is increased by raising the percentage of oxygen, and is greatest in pure oxygen. At a certain minimum concentration of oxygen, which is peculiar to any given dust, the dust is no longer inflammable. In a series of experiments carried out by the United States Bureau of Mines, the globe shown in Fig. 4

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was filled with air containing varying percentages of oxygen, carbon dioxide and nitrogen. In all the experiments, the percentage of nitrogen was maintained constant at 79, the remaining 21 per cent. consisting of mixtures of carbon dioxide and oxygen in varying proportions.

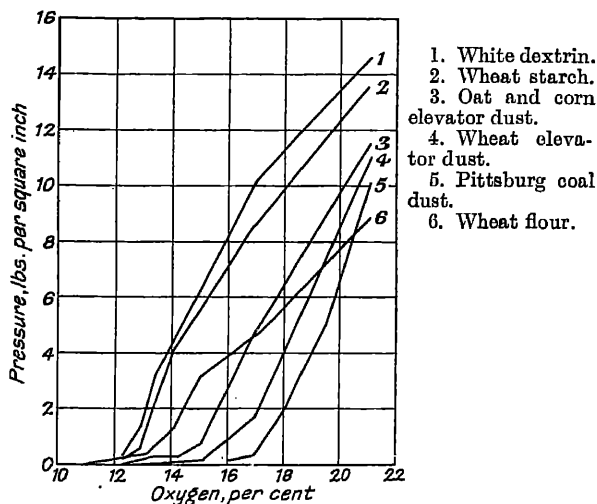


FIG. 8.—CURVES SHOWING THE RELATION BETWEEN EXPLOSION PRESSURE AND OXYGEN CONCENTRATION FOR DIFFERENT SUBSTANCES.

In Fig. 8 is shown, for a number of different dusts, the relation between the percentage of oxygen in the atmosphere and the explosion pressure. In each case, the inflammability of any particular dust, as measured by the explosion pressure, falls rapidly as the percentage of oxygen in the air is diminished. It will be noted that the

lowest oxygen concentration at which the dust can propagate ignition differs widely for different materials. Thus, wheat flour is inflammable in air which contains only 11 per cent. of oxygen, while bituminous coal dust ceases to be inflammable when the air contains just under 18 per cent. of oxygen.

It has been suggested that the explosion of dust in certain industries can be prevented by reducing sufficiently the oxygen content of the air—for example, by diluting the air with flue gas. This is done in a number of grinding plants, the flue gas being introduced into the disintegrator or mill, so that the dust that forms will be suspended in an atmosphere sufficiently poor in oxygen for combustion to be impossible. There are obvious objections to this method being applied to an atmosphere in which men or animals work, as, for instance, in a coal mine, although it was suggested by Harger that coal dust explosions could be avoided altogether in mines if the oxygen content of the mine air was reduced to 17 per cent.

It has already been shown that the inflammability of a dust is increased by the introduction of even small amounts of an inflammable gas—*e.g.*, methane or hydrogen.

(5) THE CHARACTER OF THE SOURCE OF IGNITION

From a practical standpoint, the possibility of the ignition of the dust is, perhaps, the most important consideration. The temperature of ignition—that is, the temperature to which the

source of ignition itself must be raised in order to ignite the dust cloud—depends very greatly upon the character of the source of ignition, particularly upon the area and duration of contact between it and the dust. The source of ignition possesses not only an intensity factor—its temperature—but also a capacity factor, which is measured by the quantity of heat that is emitted by it during a given interval of time. To ignite the dust particles, it is necessary to heat them up to some minimum temperature. While they are being heated, they are losing heat by radiation and conduction to the surrounding layer of the cloud. If the rate at which these particles are heated is so slow that heat is lost by radiation almost as quickly as it is received from the source of ignition, there will be little prospect of the particles reaching a sufficiently high temperature to ignite.

Clearly, heat may be communicated to such particles from the source of ignition, either by conduction or by radiation. When the source of ignition possesses a very high temperature that is of short duration—for instance, an electric spark—heat is communicated mainly by radiation, and the total amount of heat communicated to a given particle during the passage of a spark is likely to be small. If, however, the source of ignition be a luminous flame or a glowing surface of considerable extent—for example, a sheet of red-hot iron—radiation is copious and warms the particles of the dust cloud for a great distance from the source of ignition. Consequently, they become preheated and, therefore, are more readily

ignited when the wave of ignition reaches them. If the source of ignition be a non-luminous flame—for example, a Bunsen burner—or be a fairly hot surface of considerable extent, such as a bare electric-light bulb, heat is communicated to the particles mainly by conduction. The temperature of such a source of ignition is, probably, in every case very much less than that of the electric spark, but the quantity of heat that is being transmitted to the particles in a given interval of time is very much greater.

It is found, in nearly every case, that a dust cloud can be ignited more readily by such large sources of ignition at a comparatively low temperature than by smaller, much hotter sources of brief duration. It was found, for example, when ignition tests were carried out with various dusts, using as a source of ignition an electric arc, an oil lamp and a candle flame, respectively, that the dusts showed wide variation in ease of ignition and in the violence of the resulting explosion. A sample of rice dust, which was easily exploded by a candle flame, could not be ignited by an electric arc; coal dust, that ignited weakly in the arc, exploded violently with the candle flame. Flour, on the other hand, exploded readily with each source of ignition. Corn elevator dust, which was not ignited by the arc or candle flame, ignited and burned round the flame of the oil lamp, but without propagating combustion through the cloud.

In Table XXIII, the lower limits of concentration at which certain dusts explode are compared,

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using three different forms of ignition—namely, (a) a glower, consisting of a coil of platinum wire, heated to incandescence, (b) an electric arc, and (c) an induction spark. In every case, the limit is lower when the cloud is ignited by contact with the glower than it is when the cloud is ignited by contact with the arc or spark.

TABLE XXIII.—Lower Explosive Limits.

Dust.	Milligrams per litre of air.		
	Glower.	Arc.	Induction. spark.
Starch	7	10·3	13·7
Corn elevator . .	10·3	10·3	13·7
Wheat elevator . .	10·3	10·3	No "good propagation."
Sulphur	7·0	13·7	13·7
Sugar	10·3	17·2	34·4
Aluminium . . .	7·0	7·0	13·7
Coal	17·2	24·1	No ignition.

In the classification on p. 77, the lowest temperatures are given at which various dust clouds ignite when allowed to fall through a small porcelain tube that is heated to a level temperature, and containing a roll of copper gauze. In this case, propagation was facilitated, since the whole of the cloud was heated. Higher ignition temperatures—that is, a hotter source of ignition—would be required to ignite any of these dusts at a single point.

Spontaneous Ignition.—Some dusts can, in suitable circumstances, ignite spontaneously. This may be brought about by a rise of temperature due to the high rate of oxidation of the dust, or by an electric spark that is produced by the

discharge of static electricity that was resident upon the dust particles and had accumulated at some point in the system.

Thermal Ignition.—Most dusts oxidise so slowly at ordinary temperatures that the heat of oxidation is dissipated by radiation and conduction as rapidly as it is formed. Consequently, when such dusts are dispersed in the air, they oxidise without any resulting rise of temperature. They cannot, therefore, become heated spontaneously to the ignition point.

Some dusts, however, oxidise rapidly enough to become warm. Most coals, for example, when freshly mined and finely powdered, readily absorb oxygen from the air. The rate of oxidation varies with the chemical and physical character of the coal, and with the temperature at which it is exposed to the air. Of the different constituents of coal—fusain, vitrain, clarain and durain—fusain absorbs oxygen at the ordinary temperature more readily than do the others—apparently, because of some difference in physical structure. It is found in certain seams that, when coal that is adjacent to an intrusion of igneous rock is taken down, it absorbs oxygen so rapidly as to become ignited. Apparently, the heating of the coal in bygone ages by the igneous rock in the absence of oxygen has resulted in the partial decomposition and distillation of the volatile constituents of the coal. The product of this action is dry and porous, and possesses a lower specific heat than the original coal. Owing to its porous structure, the oxygen of the air readily gains access to the

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interior of the coal, and, owing to the changed chemical structure of the coal itself, it appears to be more readily absorbed.

Similarly, pyrophoric lead and iron ignite spontaneously when scattered in the air.

Spontaneous ignition due to the accumulation of heat generated by oxidation occurs more readily in aerogels, where, in a given volume, more heat is produced in a given time and less heat is lost by radiation. If a heap of bituminous coal dust be warmed from 150° to 170° F., it will oxidise rapidly enough to raise its temperature to the ignition point.

Electrical Ignition.—All dusts become electrically charged when they are blown about in the air. Since the charge resides upon the surface of the dust particles, the electrical capacity of the dust itself is proportional to its total surface area; consequently, the finer the dust, the greater will be the charge that it can carry. On the other hand, the electrical capacity of a dust *cloud* will be limited by the degree of electrical tension that can exist between the neighbouring, similarly charged particles—that is, upon the average distance that separates them from one another. Assuming that the particles of a given dust cloud are of approximately the same size and carry equal charges, the capacity of the cloud will be proportional to the number of particles per cubic centimetre—*i.e.*, to the concentration of the dust cloud and the degree of dispersion of the dust. Rudge has shown that, when the dust of any particular substance is agitated in the air, the

particles become charged by friction against one another, and, therefore, the finer the dust is, the greater will be the total charge produced upon a given mass of dust. If the total charge that is produced in this way in a given volume of a dust cloud is greater than the electrical capacity of the cloud, the system will be unstable and will discharge to some point in the system, or adjacent to it, which is at a lower potential; the spark so formed may ignite the dust cloud. The possibility of the dust cloud becoming ignited by this means will depend, therefore, upon the dielectric constant of the dust itself, and the number of particles of dust per cubic centimetre—*i.e.*, upon the concentration and the degree of dispersion of the dust; it will also depend, of course, upon the ignition temperature of the dust.

Jaekel has calculated the conditions that are necessary for spontaneous ignition of sugar dust. He finds that K , the charge per gram of the dust, is related to the different physical factors that determine the nature of the dust cloud by the following expression :—

$$K = \frac{1}{cR} \sqrt{\frac{5H \cdot dT}{4\pi} (ds_1 + cs_2)},$$

where K = charge per gram of dust, in electrostatic units,

R = radius of spherical dust cloud in centimetres,

c = concentration of dust in grams per cubic centimetre,

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dT = the difference between the ignition temperature of the dust and the temperature of the air,

H = mechanical equivalent of heat,

d = density of the air, in grams per cubic centimetre,

s_1 = specific heat of the air, in calories per gram per degree Centigrade,

s_2 = specific heat of the dust, in calories per gram per degree Centigrade.

Experimentally, the ignition temperature of sugar dust in air is found to be 410°C. , whence, by substituting values for c , H , d , s_1 and s_2 ,

$$K = \frac{10^3}{cR} \sqrt{1.42 + 2340c}.$$

By applying this expression to a spherical dust cloud, 1 cubic metre in volume—i.e., of radius $R = 62 \text{ cms.}$ —and giving various values to

R , the radius of the dust particle,

w , the weight of the dust particle in grams, assuming it to be spherical and to possess a specific gravity of 1.6,

C , the concentration of dust in grams per cubic metre,

and N , the number of particles per cubic metre,

it is possible to find the different sets of conditions that are necessary for an explosion to occur.

Assuming that the number of electrons per particle of dust is of the order of 10^3 , then particles of 10^{-4} cm. diameter will first be able to explode at a concentration of $10^4 \text{ grams per cubic metre.}$

Such a concentration is impossible in practice. Particles of 10^{-5} cm. diameter will be able to ignite at a concentration of 30 grams per cubic metre. Particles of 10^{-6} cm. diameter will ignite at a concentration of 0.03 gram per cubic metre. It is clear that the dangerous dust lies in the region of colloid dimensions, the finest dusts being by far the most dangerous. Beyersdorfer found by experiment that 1 gram of finely ground sugar dust acquired a total charge of 8.4×10^4 e.s.u. This amount of electrical energy would be sufficient to ignite the dust at a concentration of 1.57 grams per cubic metre, a concentration which is frequently obtained in disintegrators and conveyors.

THE COMBUSTION OF AN AEROGEL

Any accumulation of finely-ground material, whether in the mill itself, in the shoots or pipes leading from the mill, or in the storage bin, may be regarded as an aerogel. Aerogels are also formed when the particles of an aerosol settle out of the main body of gas and accumulate upon projecting surfaces and upon the floor.

Aerogels frequently possess a high degree of mobility, so that they surge and flow in a vessel like a limpid liquid, owing to the individual particles being "cushioned" by adsorbed gas. Good instances of this are afforded by carbon black, finely ground flint or coal, and the zinc oxide that is filtered from brass-foundry fume. In many aerogels of combustible substances, the

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particles appear to be enveloped in a film of adsorbed oxygen.

In an aerogel, the concentration of dust is very high—far above the upper limit of concentration for explosive combustion. Such a heap of combustible dust will, when ignited, burn superficially, and, if the products of combustion allow the air to penetrate readily to the unburnt portion of the dust, combustion will spread gradually through the mass.

Sinnatt and Slater have shown that the readiness with which a “zone of combustion” is propagated through a heap of coal dust is determined by (1) the character of the coal, (2) the fineness of division and (3) the amount of inert material present. They found that combustion could not be propagated unless the particles were smaller than a certain critical value, which was different for different samples of coal. In the cases considered, from 80 to 90 per cent. passed 200 mesh. Evidently, the specific surface of the dust is a deciding factor—possibly, because it determines the degree of intimacy with which the particles come into contact with one another and with the air.

The combustion of the coal dust was restricted to the surface of the particles. This is probably typical of the combustion of an aerogel, and is due to the relatively limited supply of oxygen.

Of the different constituents of coal, fusain promoted combustion most readily; even coarse coal dusts (60-mesh), that would not burn alone, would propagate readily when mixed with 30 per

cent. fusain. It is interesting to note that the coal dust that occurs in mines frequently contains up to 49 per cent. fusain, although the coal from which the dust is formed may contain as little as 2 per cent. fusain.

It was found that the addition of more than 52 per cent. stone dust completely prevented the ignition of the coal dust; at that percentage and below it, combustion spread gradually through the heap.

If an aerogel that is burning superficially suddenly becomes distributed throughout a relatively large volume of air, the aerosol that is so formed will become ignited by the burning dust, and, if suitably concentrated, will explode. Explosions have been caused in mills by the ignition of a dust deposit on a girder—for example, by a spark. The smouldering dust has then fallen from the girder, and become mixed with sufficient air to form an explosive mixture, which has instantly been ignited by the burning dust particles.

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CHAPTER VII

DUST EXPLOSIONS IN FACTORIES

Two things are necessary to cause a dust explosion—namely, the production of a dust cloud, of concentration lying within the explosive limits, and the introduction of an effective source of ignition. Either of these conditions may occur without the other—in fact, frequently does—without producing any explosion. In many cases, it is only after a comparatively long period of apparent immunity that both the dust cloud and a suitable source of ignition occur simultaneously and produce an explosion.

The dust cloud may be formed gradually (for example, by the continuous escape of dust from a disintegrator into the surrounding air), or it may be formed suddenly (for instance, by the fall of an accumulation of dust from a girder, by the stirring up of dust deposited upon the floor, or by the movement of the ground product in the disintegrator itself, in conveyors or elevators, or in storage bins).

During the gradual production of a dust cloud, the concentration of dust in the air increases relatively slowly and, owing to the simultaneous settling of the dust upon the floor, walls and machinery, it may never reach an explosive value. In most cases, the rate at which the dust is removed from the immediate point of production by draughts and convection currents, and by subsequent settling, is sufficient to prevent an explosive concentration being reached—particularly, as many materials contain a high proportion of incom-

bustible matter and will not explode until a high concentration is reached.

In many factories, work is carried on—apparently with impunity—in a persistent haze of fine dust. It may be that the concentration of dust in the haze does not ordinarily reach the explosive limit; at the same time, the presence of dust in the air necessarily results in dust accumulating on exposed surfaces, and if, at any time, such an accumulation of dust becomes disturbed, it will form a cloud that will almost certainly be explosive. If such a cloud should come into contact with a suitable source of ignition, it will explode. The initial explosion will disturb other dust accumulations, which, in turn, will become ignited, rapidly causing widespread disaster. Probably the most frequent cause of dust explosions is the sudden production of such a dust cloud in circumstances that promote its ignition. It is impossible to prevent dust clouds from forming in any enclosed space in which the finely-ground product is continually being disturbed—for example, in disintegrators, in conveyors, elevators, storage bins; it is, however, nearly always possible to restrict the escape of the dust into the air, and the consequent accumulation of dust on exposed surfaces.

IGNITION

It has been found, in practice, that the ignition of a dust cloud can be brought about by—

- (a) open flames or fires;
- (b) overheating of the dust;

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- (c) sparks ;
- (d) electric arcs ;
- (e) electric sparks.

(a) **Open Flames or Fires.**—These are generally due to carelessness or ignorance on the part of the workmen. A workman may go into an empty bin or elevator housing to inspect it or clean it, or to do some repairs, and may strike a match or carry an open lamp. He may shovel or brush dust from the floor or sides, or raise the dust with his feet. In either case, the dust forms a cloud which is ignited by the open flame and explodes violently. Numerous cases are on record where workmen have used open flames to inspect the contents of bins and elevators when they were in action. In some cases, the ignition is due to the accidental breaking of an otherwise protected lamp—for instance, a bare electric-light bulb. In other cases, ignition has been due to the close proximity of gas engines or steam boilers, etc., to the room in which milling operations were carried on, a cloud of dust being carried by a draught to the neighbouring open fires. Frequently, a dust explosion has followed upon an outbreak of fire, the dust being raised by the collapse of some portion of the burning building, and ignited by the flames.

(b) **Overheating of the Dust.**—Dust may become heated by an overheated bearing, by contact with an unprotected electric-light bulb, or a heated metal surface—for example, the partition wall between the grinding room and an adjacent boiler plant. Frequently, overheating of the dust has

been caused by friction in the disintegrator itself when, for some reason or other, the delivery pipe has become choked and the contents have remained in the mill too long. Many fires and explosions have been caused in grain elevators by the choking of the elevator head and the consequent heating of the grain by friction with the driving shaft.

(c) **Sparks.**—Sparks are a frequent cause of explosion in attrition mills and disintegrators. The sparks may be produced either by the friction of the opposed grinding faces of the mill when, for any reason, the feed has been cut off and the mill is running empty, or to the accidental introduction of some piece of iron or other hard material. Occasionally, explosions have been caused by sparks due to pieces of iron, or stones, striking the blades of the exhaust fan that removes the dust-laden air. The sparks that are struck by workmen's tools are also a possible source of ignition.

(d) **Electric Arcs.**—An electric arc of high temperature and of considerable extent and capacity is frequently formed when the fuse of an electric motor blows out. Arcs may also be caused by faulty wiring, leading to short circuits and broken connections. Sometimes, the arc and the dust cloud may be produced simultaneously by the same cause. One of the greatest dust explosions that took place in this country was attributed to the ignition of a dense cloud of dust that was produced by the breaking of the driving belt of a disintegrator. The breaking of the belt stirred up a cloud of dust, which was ignited by

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the arc formed by the blowing out of an uncovered fuse on a temporary switchboard.

(e) **Electric Sparks.**—We have seen that electric sparks may be produced by the discharge of static electricity that has accumulated on the moving parts of machinery or on the dust itself. Explosions have frequently been produced in this way during the threshing of grain in the west of America, where the atmospheric humidity is often very low, and frictional electricity accumulates rapidly on the driving belt and other parts of the threshing machine.

Some dusts—for example, sugar, aluminium and sulphur—readily become charged by friction with the air and with grinding surfaces, and may, under suitable conditions, become sufficiently highly charged to produce a spark that will ignite the dust.

THE PREVENTION OF DUST EXPLOSIONS

In practically all cases, it is possible to adopt suitable measures to prevent the occurrence of a dust explosion. The choice of method necessarily depends upon the nature of the process, the design of the plant, and the character of the product; in a coal mine, for instance, the dust can be kept wet with water, or it can be rendered inert by the liberal addition of stone dust; obviously, however, these methods would be of no value in a flour mill. Similarly, methods which depend upon the dilution of the air with an inert gas would be totally unsuitable for use in a coal mine.

By far the safest and most satisfactory method

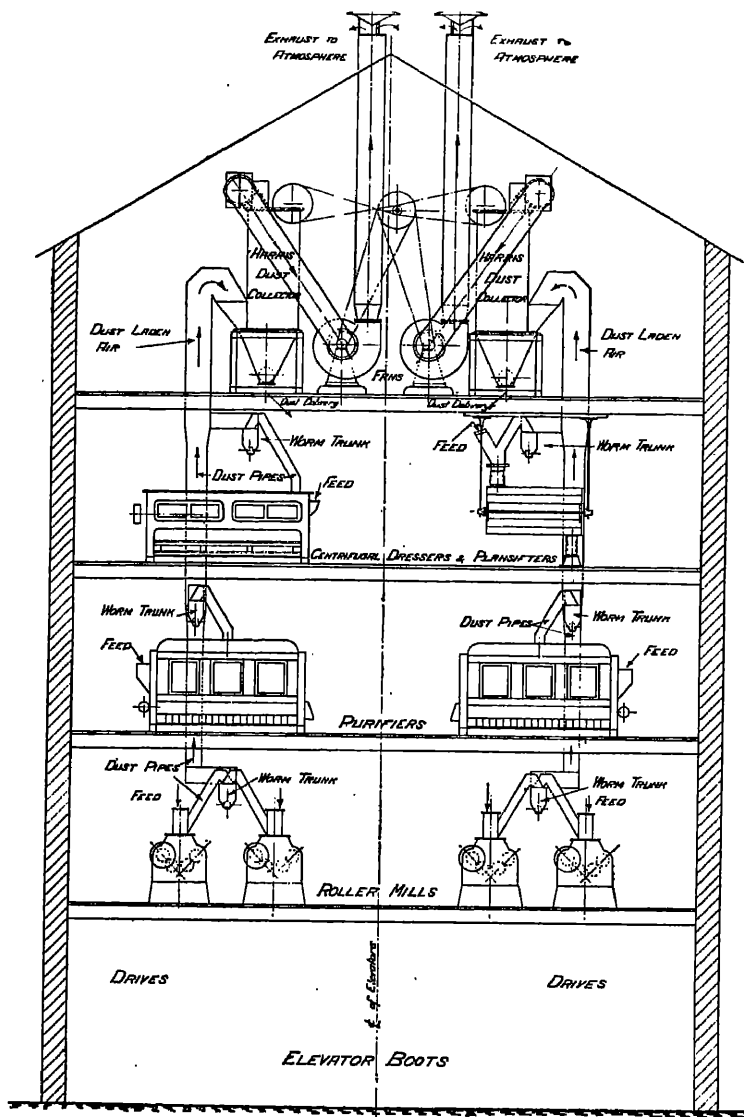


FIG. 9.—GENERAL ARRANGEMENT SHOWING MEANS FOR PREVENTING THE ESCAPE OF DUST IN A MODERN FLOUR MILL.

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of preventing dust explosions is to do all that is humanly possible to prevent the formation of the dust cloud and to eliminate all possible sources of ignition. In wood-working plant, disintegrators, screening or conveying plant, etc., dust is collected at its source by means of suitable suction hoods that are set as close to the work as possible, and are connected through a piping system to an air filter and an exhaust fan. The arrangement of such a system is shown in Figs. 9 and 10.

A great deal can be done, and is being done, to prevent the escape of dust into the air by using milling and grinding machines of a totally enclosed type that renders them practically dust-tight. Where this is not convenient, the machine is housed in a dust-tight enclosure or room, from which the dusty air is extracted by a fan.

In all such arrangements, it is essential that the fan should be situated beyond the filter, so that only dust-free air comes into contact with it. In more than one instance, a dust explosion has been caused by a spark from the fan igniting the dusty air that was passing through it. Such a spark may be caused by a blade coming into contact with the fan-casing, or *by the sudden contact* of some foreign material, carried in the air stream, with a blade of the fan. An additional advantage of exhausting the dusty air through a suitable bag filter is the recovery of the dust—particularly when the dust is valuable.

Even where proper precautions are taken to prevent dust accumulating in sufficient quantities to form an explosive mixture, there is always the

possibility that something may go wrong with the arrangements, and that an explosive mixture may be formed and become ignited. It is necessary, therefore, to guard against even the remotest chance of ignition.

We have seen that a dust cloud may be ignited by open flames, by contact with heated surfaces, and by electric arcs and sparks. A common source of ignition is a spark produced in an attrition mill by the introduction of some foreign substance—for example, an iron bolt or nail—or by the interruption of the feed, so that the mill runs dry and the grinding faces rub against each other. Foreign substances can be eliminated from the feed by subjecting it to a preliminary pneumatic or magnetic separation as it goes to the storage bin or to the mill itself.

In pneumatic separation, the feed is discharged from a shoot or conveyor into a blast of air which blows it into an adjacent bin. Any unduly heavy particles, large or small, fall short of the bin and are collected in a box placed just below the point of discharge. Magnetic separation is effected by passing the feed over strongly magnetised plates. In some cases, the material is conveyed on a belt that passes at the discharge end over a strongly magnetised pulley. Any pieces of iron or steel that may be in the feed are held back by the magnetised surface or are delivered into a separate receptacle.

Dust is sometimes heated to the ignition point by friction. This occurs in an attrition mill, if the free discharge of the ground product becomes

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interrupted, or in a grain elevator when the outlet spout becomes choked and the pulley revolves in the accumulated grain. The mill should be so arranged that if, for any reason, the flow of the feed either to or from the mill is stopped, the mill stops or the grinding surfaces are automatically thrown apart. Various devices have been designed to prevent the choking of elevators. The most satisfactory arrangement is to provide it with a second discharge spout that will return the product to the elevator boot. The mouth of this spout is set higher than the other, so that it only comes into action if and when the ordinary discharge spout becomes choked.

Whenever possible, the use of open flames, such as matches, candles, oil lamps and gas lights, should be rigidly prohibited. The only really safe form of lighting is electric lighting, using specially protected bulbs. Any flame such as that of an oil lamp or gas light, even when protected by the chimney or globe, necessarily depends upon air for its combustion, and, if the air that is drawn into it is dusty, it may become ignited, and communicate ignition to the surrounding dusty air. Electric gas-filled lamps may be a source of danger if, as sometimes happens, the light, fluffy dust is allowed to collect upon the bare lamp, and become heated. This danger can be avoided by enclosing the lamp within a glass, weather-proof fixture. When this is done, gas-filled lamps of up to 200-watt capacity may be used with safety. The use of such a stout, weather-proof fixture also reduces the risk of breakage, but it would, no doubt, be

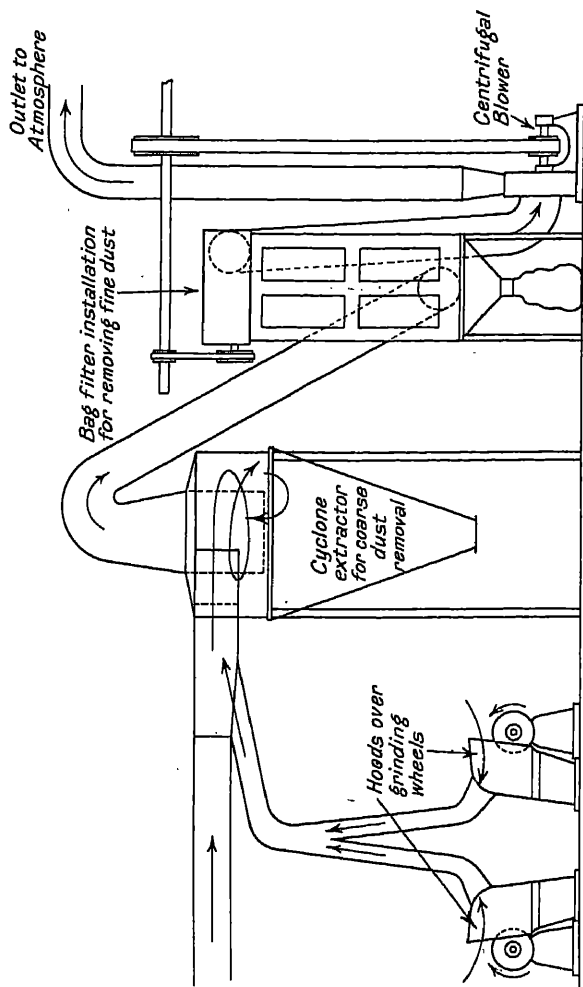


FIG. 10.—ARRANGEMENT OF SUCTION HOODS AND EXHAUST FROM GRINDING MACHINERY.

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better if this weather-proof fixture were further protected by means of a wire cage.

Since a dust cloud, formed in the immediate neighbourhood of the grinding plant, for example, may be carried by draughts to neighbouring parts of the factory, it is desirable, when designing the arrangement of the plant, that steam boilers, gas producers, gas engines and oil engines should not be placed in rooms or in parts of the premises which communicate directly with the grinding room or with any room in which a dust cloud might be generated.

Since the effect of heated surfaces depends upon the accumulation of dust upon them, the danger arising from such a source of ignition can be completely avoided by keeping the surfaces clean. In many cases, where it is impossible to prevent an escape of dust into the air, the accumulation of dust upon exposed surfaces can be prevented by maintaining an efficient and continuous system of vacuum cleaning. This is the only satisfactory method of removing deposited dust. It avoids the formation of the dust cloud that ordinarily results from the disturbance of deposited dust by brooms or compressed air.

The danger of ignition arising from electric arcs that are produced by the blowing of a fuse, by a faulty contact, or by leaks, can be eliminated by using properly designed motors, fuse-boxes and switch-boxes of the enclosed type, and by paying attention to the character of the wiring installation. In most cases, this is now done very thoroughly, but, in some old installations, the character of the

wiring leaves very much to be desired. The production of sparks by the accumulation of static electricity upon belts and other moving parts can be prevented by arranging suitable earthed connections to carry away the electricity as quickly as it forms.

In Fig. 11 are shown diagrammatically two

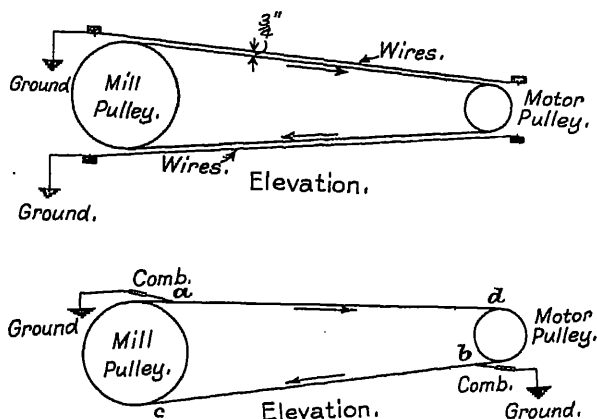


FIG. 11.—DEVICES FOR REMOVING STATIC ELECTRICITY FROM DRIVING BELTS.

simple devices for removing static electricity from driving belts. The first consists of a pair of grids of copper wires, placed both above and below the belt at a distance from it of about three-quarters of an inch. The grids are well earthed. Repeated trials in varying conditions of humidity have shown that, when these grids are in position, no electricity can accumulate upon the belt.

In the second arrangement the electricity is

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collected by two combs that press firmly upon the outer surface of the belt just after it leaves the pulleys. The combs are well earthed. They can be made by soldering pieces of stout brass wire to a strip of galvanised iron. It is found that, so long as the combs are placed at *a* and *b*, no charge is found upon the belt, but, if the combs are placed at *c* and *d*, the belt becomes charged. It is necessary to keep the combs continually in contact with the belt; otherwise, sparks will be formed which, in a gaseous or dusty atmosphere, may cause disaster.

Static electricity may also accumulate upon the fabric of bag filters through which electrified dusty air—for example, from a sugar mill—is being filtered. The bags should be lined on the dusty side with an open network of copper wire that is connected to earth; otherwise, a spark may form and ignite the contents of the bag.

Static electricity only accumulates to a dangerous extent in a dry atmosphere. It is commonly avoided by humidifying the atmosphere. In this country, during the greater part of the year, the air is too humid for it to accumulate to any great extent.

It is not always possible to prevent the formation of a dust cloud. Such clouds are constantly being formed in the actual mills and disintegrators, and in the housing of conveyors or elevators, and in bins, and also in such places as coal mines, where the dust accumulates along the workings and is continually being disturbed by the traffic. The

dust cloud can be rendered inert either (a) by diluting it with inert gas (*e.g.*, flue gas) or (b) by diluting it with an inert dust (*e.g.*, stone dust). Of these two methods, the former, generally speaking, is suitable for use in enclosed spaces and factories, the use of the latter being almost entirely confined to coal mines.

It has been shown in Fig. 8 that the inflammability of various dusts is greatly reduced by reducing the oxygen content of the air, and, indeed, if the oxygen content is reduced sufficiently, the dust can no longer be ignited. As the result of tests carried out by the United States Bureau of Mines, it is considered that, if the oxygen in the atmosphere of any enclosed system in which grain is ground or handled is maintained below 14 per cent., there will be no risk of explosion. This can be done by maintaining an atmosphere of flue gas in contact with the dust.

The flue gas is drawn from the boiler stack and, after passing through a scrubber and moisture traps to cool it and to remove dust and excess moisture, it passes through a measuring device. It is then conducted into the milling machine along with the grain, then into the various conveyors to the elevator and bin, and, finally, from the bin, it passes to the outside air. It will be necessary to make the housing of the mill and conveyors reasonably gas-tight, although, probably, an ordinary mill would be so well ventilated that the escape of inert gas from the housings would not appreciably affect the purity of the atmosphere.

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In carrying out such a process, it is necessary to record and control the composition of the flue gases, so that the proportion of oxygen in contact with the grain never exceeds 14 per cent.

The method is open to two objections. In the first place, there is the possibility of carbon monoxide being present in the flue gases and escaping into the mill atmosphere. The amount of carbon monoxide in flue gas containing from 10 to 12 per cent. of oxygen is generally much less than 1 per cent., and, in a properly designed installation, there is no reason why it should escape into the atmosphere to such an extent as to be harmful to the employees. Another objection which was raised was the possible effect of some constituent or constituents of the flue gas upon edible products such as flour, etc. Experiments were carried out, using both washed and unwashed flue gas, and it was found that washed gas had no effect upon dextrin, starch or flour. If the gases were not well washed, there was a tendency for the flour to absorb some of the impurities, and to acquire a tarry odour. It would be necessary, also, to take great care to eliminate all possibility of arsenic being present in the flue gases. Provided, however, that the gas be sufficiently well washed and purified, its use in this way should be both possible and desirable. It can only be used in enclosed places such as those mentioned, but as, in so many cases, explosion has spread along ducts and elevator housings in which such a method could be employed, it is evident that increased safety could be obtained by adopting it.

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PREVENTION OF THE SPREAD OF EXPLOSION

In many cases, the damage that is done by an explosion is caused, not by the primary explosion, but by the widespread extension of the explosion through the progressive raising and ignition of the dust throughout the factory. The spreading of the explosion can, where possible, be prevented by keeping the factory free from dust. It is obviously impossible to adopt this precaution in enclosed places in which the dust is being conveyed. A primary explosion may, for instance, occur in a grinding mill, and may spread through the shoots or conveyors leading from the mill to a storage bin.

Various devices have been introduced for preventing the spread of the explosion through the conveying system. The two most generally used are the explosion damper and the so-called "choke" conveyor.

The action of the explosion damper is illustrated in Fig. 12. The explosion damper is placed between the attrition mill and the conveyor. It is rotated by gearing connected with the conveyor drive, and is so constructed that in any position it forms an effective seal separating the contents of the mill from the contents of the conveyor. A similar explosion damper placed at the delivery end of the conveyor serves to separate it from the bin. A vent pipe should be situated just in front of each explosion damper. If an explosion occurs between two explosion dampers, it will exhaust itself through the vent pipe. It is important, therefore, that the vent pipe should be as straight

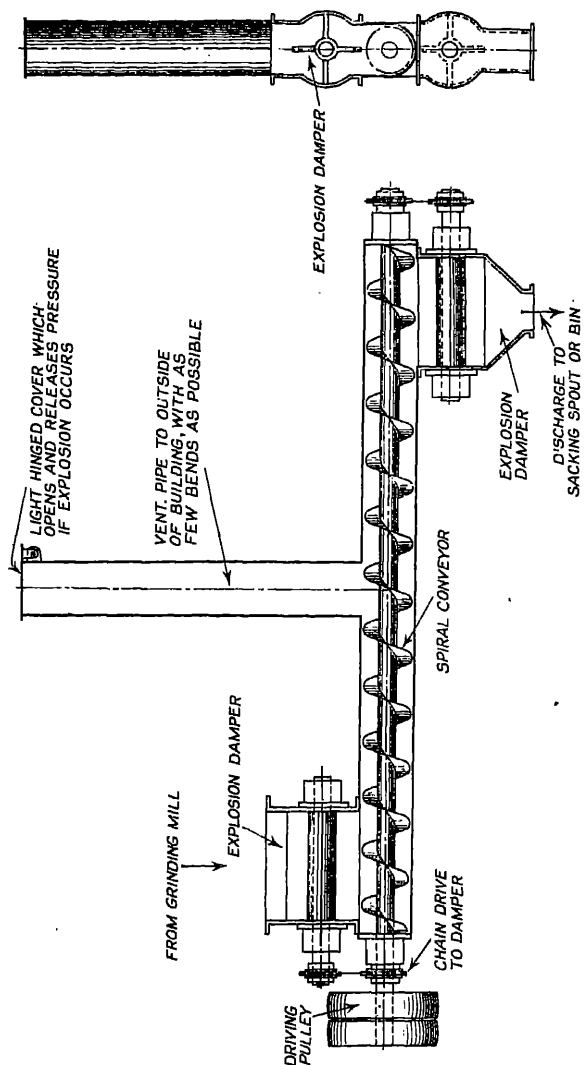


FIG. 12.—DIAGRAMMATIC VIEW OF EXPLOSION DAMPERS AND VENT PIPE.

as possible, so that it offers a minimum of resistance to the passage of the explosion to the outside air. It has been shown repeatedly that the installation of one such damper in a system will prevent the spread of minor explosions; if two dampers are used in series, they will be sufficient to prevent the spread of most explosions.

The "choke" conveyor is a screw conveyor in which a number of the flights at the discharge end of the screw have been removed; consequently, material fills up the conveyor at this end, and can only be discharged by being displaced by the material that is coming along behind it. In this case, therefore, the conveyor itself serves as an explosion damper. A vent pipe should be placed in proximity to each choke conveyor.

A German patent describes a device to prevent the spread of explosion in a conveying system by the use of inert dust. The inert dust is contained in a specially designed chamber that is placed above the conveyor housing, and opens into it through a flap valve. Ordinarily, the valve remains closed, but if an explosion occurs, the force of explosion acts upon a swing damper placed at the end of the conveyor housing, and either diverts the explosion through a vent pipe to the outer air, or releases the inert dust, which falls in a dense cloud into the conveyor and quenches the flame.

PROTECTIVE LEGISLATION

As a direct result of the investigations that have been carried on into the origins and characteristics of dust explosions during recent years, legislation

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has been introduced in this and other countries with the object of reducing the risk of dust explosions as completely as possible. The following list of recommendations, made by His Majesty's Inspector of Factories to apply to grain-storage warehouses and other places where inflammable dust is generated in dangerous quantities, effectively summarises the various precautionary measures that are at present available for preventing dust explosions.

(1) Rooms used for the purpose should not have other rooms above them, nor should they be adjacent to higher buildings which would be affected in the event of an explosion.

(2) The roof should be such as to offer little resistance in the event of an explosion.

(3) There should be no open beams, girders or other ledges or projections on which dust could lodge.

(4) The floors, walls, machinery, appliances and any ledges, as above, should be cleansed from dust daily—preferably, by a suction cleaner.

(5) Underground rooms are unsuitable for disintegrators or other grinding machinery.

(6) All grinding and mixing machines, hoppers, elevators, worms and conveyors (other than belt conveyors—see below) should be so constructed as to prevent the escape of dust, and preferably provided with exhaust draught. Belt conveyors should be provided with exhaust draught and adequate appliances for interception and removal of dust at the points where they are filled and discharged.

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(7) Efficient electro-magnetic separators should be provided on the feed of each disintegrating or other grinding machine to arrest particles of iron or steel.

(8) No naked gas lights or electric arc lamps should be used in such rooms; and incandescent electric lamps should have outer dust-tight covers.

(9) In such rooms, Regulation 27 of the Electricity Code (see definition which follows later) requires special protection of conductors, switches, fuses and other electrical apparatus.

(10) No matches or smoking should be allowed.

(11) In connection with grinding and cleaning machinery, the use of a stive room is unnecessary and dangerous; more modern methods of intercepting the dust, such as cyclone collectors or bag filters, should be substituted.

The possibility of dust being ignited by electrical means is dealt with in the following recommendations of His Majesty's Electrical Inspector of Factories :—

“ Regulation 27 of the Electrical Regulations should be regarded as applying in this case; this regulation requires :—

“ All conductors and apparatus exposed to the weather, wet corrosion, inflammable surroundings or explosive atmosphere, or used in any process or for any special purpose other than for lighting or power, shall be so constructed or protected, and such special precautions shall be taken as may be necessary adequately to prevent danger in view of such exposure or use.”

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"A dust cloud might be ignited through (1) the bursting of an incandescent lamp; (2) overheating of conductors or apparatus by (a) excess of current, (b) bad joints or connections; (3) inadequate protection of conductors and apparatus resulting in sparking; (4) arcing of apparatus needed for breaking circuits such as switches, circuit breakers, fuses and connectors for portable lamps.

"It is, of course, obvious that no lamps should be used except those of the vacuum type, and with regard to :

"(1) Such lamps should be enclosed in stout outer protecting glasses with rubber or other joints as nearly as possible dust-tight—this applies equally to portable hand lamps.

"(2) This matter is covered by the requirements of previous regulations.

"(3) For the protection of cables and wires, the use of heavy gauge screwed metal conduits is recommended, care being taken that the conduits are electrically continuous and earthed.

"(4) As arcing or sparking of the contacts of switches, circuit breakers or fuses cannot be prevented, means should be adopted to render the dust harmless by enclosing them in dust-tight covers or placing them where there is no danger of firing the dust; the switch covers should be dust-tight, and the fuses should be of a type which will not cause an explosion."

For further detailed information and numerous descriptive records of dust explosions in factories, see "Dust Explosions," by Price, Brown and Roethe. (National Fire Protection Association, Boston, Mass.)

CHAPTER VIII

DUST EXPLOSIONS IN MINES

THE conditions that obtain in a coal mine differ in many important respects from those in a factory, both in the manner in which the dust is produced and ignited, and in the character of the resulting explosion.

Coal-mining is necessarily a dusty occupation. Coal is brittle and friable and, when broken either by picks or by blasting, readily produces a considerable quantity of fine dust. This dust is carried along the workings by the ventilating current and is deposited upon the floor, roof and sides of the galleries. It is produced by the traffic along the roads and is shaken from the moving tubs, unless they are specially constructed to prevent it. Where the screening plant at the surface is situated near the mouth of the down-take ventilating shaft, a large amount of coal dust is carried down into the mine by the ventilating current. Some dust accumulates on timbers and ledges, from which it may be dislodged suddenly at any time to form a cloud that is carried along the workings for a considerable distance before it settles. The dust that has accumulated on the floor is constantly stirred up by passing trucks.

The walls of a mine are better adapted than those of a factory building to withstand the sudden pressure of an explosion. Consequently, the material damage that results from an explosion in a mine may often be small, when compared with the general wreckage of factory buildings

that is produced often by a relatively slight explosion. In a mine, however, the explosion spreads with devastating force along the workings, leaving death and destruction in its wake.

All mines are necessarily dusty: the dust accumulates along the workings and is constantly being raised by traffic, so that a condition of risk is continually being caused. It is impossible to keep the mine free from dust, or to dilute the atmosphere with inert gas. It is necessary, therefore, in coal mines to adopt other means of prevention.

Of various factors that combine to produce a coal dust explosion, the most important are :—

- (1) The chemical and physical nature of the coal.
- (2) The concentration of coal dust in the atmosphere of the mine.
- (3) The fineness of the dust.
- (4) The composition of the mine atmosphere.
- (5) The velocity of the pioneering explosion wave.

(1) THE CHEMICAL AND PHYSICAL NATURE OF THE COAL

Percentage of Volatile Matter.—Coal is more inflammable, the greater the percentage of volatile matter that it contains, although the *quantity* of volatile matter does not completely determine the inflammability. It is found that the character of the volatile material, particularly the rate at which it is evolved when the coal is exposed to radiant heat, is equally important.

Taffanel and others have shown that, above 25 per cent., variations in the amount of volatile matter do not appreciably affect the ease of ignition. Below this value, however, every 1 or 2 per cent. decrease results in a considerable reduction in inflammability. Coal containing less than 11 per cent. of volatile matter may be considered to be relatively safe. Anthracite dust is practically non-inflammable. No explosion of dust has been known to occur in an anthracite mine, and even when explosions of gas occur, they are of relatively short duration and limited extent. In practically every instance of a coal dust explosion, the coal is bituminous or semi-bituminous, containing from 15 per cent. to 45 per cent. of volatile matter.

Ash and Moisture Content.—The amount of incombustible matter that is present in the coal necessarily reduces the quantity of available combustible matter, and, therefore, reduces the inflammability of the dust and the risk of explosion. It has been shown, for example, that a bituminous coal dust containing 14 per cent. ash readily exploded, but that, as the ash content was gradually increased by the addition of an inert dust, the violence of the explosion diminished until, when the dust contained 48 per cent. ash, it was no longer explosive. This is due to the absorption of heat by the incombustible matter, so that the temperature of the combustible portion of the particles is raised to a correspondingly smaller extent, and ultimately fails to reach the ignition temperature at all.

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In a similar way, moisture absorbs some of the heat, utilising it as latent heat of evaporation, long before the temperature of the combustible portion has reached the ignition point, and, therefore, diminishes the inflammability of the dust. Coal, when freshly cut, contains from 0.5 to 10 per cent. of moisture in bituminous coals, and up to 30 per cent. or even more in lignites. Experiments that have been carried out in America have shown that the presence of 30 per cent. of water will render any bituminous coal dust non-explosive, although, in many cases, less than half this quantity is sufficient. In most cases, the moisture content of coal dust in the mine is too small to have any serious restraining action upon the inflammability of the dust. Lignites, although they contain more volatile matter than bituminous coals, are less readily ignited, because of their naturally high moisture content.

(2) THE CONCENTRATION OF COAL DUST

A relatively small amount of coal dust can propagate combustion. Three ounces of bituminous coal dust, containing 4 per cent. of ash, 30 per cent. of volatile matter, and passing completely through a 200-mesh sieve, will, when suspended in one cubic yard of air, ignite readily and burn explosively. Frequently, attempts have been made to prevent the spread of an explosion in a mine by maintaining so-called dustless zones. These zones consist of lengths of gallery of about 1000 feet, from which all dust is carefully removed at least once a day. It is found, however, that

the small amounts of dust that are inevitably left on crevices and on ledges, after such cleaning operations, are sufficient to propagate explosion.

The minimum concentration of dust that is necessary for the propagation of an explosion is higher when the coal contains more ash or less volatile matter. It is less when the air contains methane. If the concentration of coal dust is increased beyond a certain maximum value, the mixture is unable to propagate flame.

(3) THE FINENESS OF THE DUST

Like other combustible substances, coal dust explodes more readily, the more finely it is divided. The relation between the fineness of the dust and the ignition temperature of the dust cloud is shown in the following table.

TABLE XXIV.

Fineness of dust.	Ignition temperature.	Percentage of ash in sample.
1/100 to 1/150-mesh sieve.	2463° F. (1350° C.)	1.50
1/150 to 1/180- "	1652° F. (900° C.)	1.57
1/180 to 1/220- "	1562° F. (800° C.)	1.80
Through 1/220- "	1362° F. (850° C.)	1.98

Very fine dust ignites more readily, partly because the area of contact between the dust and the oxygen is so great; also, it is probable that, with such finely-divided dust, a considerable proportion of the particles will be sufficiently small to exhibit Brownian motion. They will thus act like very sluggish gas molecules, and, by facilitating communication between neighbour-

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ing particles, promote the propagation of combustion through the cloud.

(4) THE COMPOSITION OF THE MINE ATMOSPHERE

The ease with which coal dust ignites and burns depends very much upon the proportion of oxygen in the atmosphere, and upon the amount of methane that may be present. It ignites less readily if the percentage of oxygen in the air is reduced. It has been shown that coal dust cannot be ignited in air that contains less than 18 per cent. of oxygen.

The presence of small proportions of methane, however, greatly increases the inflammability of coal dust, rendering it explosive even when the concentration of dust or of oxygen is below the requisite minimum value. It increases the violence with which explosion occurs.

(5) THE VELOCITY OF THE PIONEERING WAVE

When an explosion occurs at any point in a mine, the pressure wave that is set up travels along the workings in advance of the wave of ignition, and, if sufficiently violent, raises the coal dust from the floor and walls to form a dust cloud that, in most cases, will be explosive. To raise dry coal dust, the wave velocity must be greater than 17 miles per hour. In experiments at Altofts Colliery, air velocities of up to 1300 miles per hour have been recorded, while the lowest recorded velocity exceeded 100 miles per hour. Clearly, therefore, if an explosion occurs, it will itself produce the conditions that will promote its progress through the mine.

IGNITION

For an explosion to occur, two things are necessary: the presence of an explosive mixture of dust and air or of methane and air, and the production of a sufficiently high temperature. In most cases, probably, the mixture becomes ignited by the firing of a shot. Even when permissible explosives, burning with a short flame of brief duration, are used, an excessive charge may be used or it may be tamped with coal dust. In the first case, the shot would blow out and ignite any dust in its vicinity. When tamped with coal dust, the firing of a shot would eject the coal dust into the air and produce the conditions necessary for the starting of an explosion. Ignition may also be caused by firing the shot improperly, or it may fire into a pocket of gas. In spite of all disciplinary caution, ignition has been caused by the striking of a match, or by the use of an open or defective safety lamp. In many so-called non-gaseous mines, open lights are used freely, and shots are fired with black powder or dynamite. In America, where electric trolley-haulage is widely used, gas or dust may be ignited by an electric spark, particularly when the trolleys operate in return-airways—that is, in air charged with dust or gas, or both.

THE PREVENTION OF COAL DUST EXPLOSIONS

From a consideration of the foregoing brief summary of the conditions that determine the explosion of a cloud of coal dust, various methods of prevention suggest themselves:—

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(a) Prevent the accumulation of dust in the workings by continually removing it as it is produced.

Experiments carried out by the American Bureau of Mines show that, after a thorough cleaning of the mine with shovels, brushes, and jets of compressed air, assisted by a strong air current moving in the direction of the cleaning, there will still be enough coal dust left in the average mine to propagate an explosion. An explosion was started by means of a coal dust zone a few hundred feet long, and, in this test, the explosion swept violently through the supposed dustless zone, which was a thousand feet long and had just been cleaned.

(b) Reduce the oxygen content of the mine air.

Harger showed that coal dust would not ignite in air containing 18 per cent. of oxygen and 72 per cent. of nitrogen, and suggested that the mine air should be diluted with flue gas sufficiently to reduce its oxygen content to 17 per cent.

When methane is present, the dust ignites more readily, so that, if ignition is to be prevented, the oxygen content must be reduced still further. If 2 per cent. of methane be present, coal dust will ignite in air containing just over 16 per cent. of oxygen. If the oxygen content of the air is reduced to 13 per cent., neither methane nor coal dust, either separately or together, will burn in it.

Since methane-air mixtures of almost any composition may occur in a mine and, becoming ignited, initiate an explosion, it would be necessary—particularly in a gaseous mine—to reduce the

oxygen content of the mine air to 13 per cent. It is doubtful whether air containing even 17 per cent. oxygen would afford a fit working atmosphere for men and animals.

(c) Keep the dust wet with water. This will prevent it from being easily disturbed by air currents, and will also raise its ignition temperature.

Wetting has been, and still is, widely used. It is unreliable, because :—

- (i) fresh coal dust is not easily wetted by water;
- (ii) when thoroughly wetted, the dust is soon dried by the ventilation current—particularly in cold, dry weather;
- (iii) watering may be carried out carelessly. One of the greatest coal dust explosions in America was attributed to failure to water the mine after a holiday.

(d) Increase the percentage of incombustible material in the dust.

This can readily be done by distributing a suitable inert dust throughout the mine. Of recent years, the stone-dusting of mines has been thoroughly investigated in this and other countries, and has been widely adopted. It constitutes by far the greatest advance for generations in the attempts that have been made to safeguard the workers in this industry from the awful and devastating consequences of explosion.

THE STONE-DUSTING OF COAL MINES

In 1908, Sir W. E. Garforth demonstrated, in a small experimental gallery at Altofts, that fine

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stone dust will check an explosion of coal dust. The efficacy of stone dust was fully investigated on a large scale, first of all, at Altofts, during 1908-1909 by the Mining Association of Great Britain, and, subsequently, at Eskmeals by the Government. In 1914, the Explosions in Mines Committee, as a result of these investigations, reported that—

“The experiments which have been carried on at Eskmeals during the past three years, the results of which have been set out in the six reports submitted by us, establish, so far as experiments can, that :—

“(i) The maintenance throughout the roads of such a proportion of incombustible dust in a state of fine division as would make a mixture yielding, on incineration, at least 50 per cent. of ash; or

“(ii) The maintenance of at least 30 per cent. of water in a state of intimate mixture with the dust throughout the roads; or

“(iii) A combination of the two previous methods—*i.e.*, the treatment of the roads first with incombustible dust and then with water,

would prove effective in very greatly minimising, if not preventing, explosions of coal dust.”

These findings were adopted by the Home Office, and embodied in General Regulations issued in July, 1920.

In carrying out these regulations, the following conditions must be considered :—

- (1) The *floor, roof and sides* of every road or part of a road which is *accessible* must be *treated with incombustible dust* in such a manner, and at such intervals, as will ensure that the *dust on the floor, roof and sides throughout* shall *always* consist of a mixture containing *not more than 50 per cent. of combustible matter*. Although it is not stated in General Regulation 2 (a), General Regulation 4 (c) indicates that the percentage of combustible matter in the mine dust is to be reckoned by weight and not by volume.
- (2) The incombustible dust used must contain not less than 50 per cent. by weight of fine material.
- (3) The incombustible dust must not be injurious to the health of persons working in the mine.
- (4) The *floor* of every *travelling road* must be *cleared of dust at regular intervals of time*, so as to keep it free from all accumulations of dust.
- (5) The Regulations do not apply to the face, or to roads, or parts of roads, within 10 yards of the face.

The Regulations leave the colliery management free to adopt any system or systems of application, provided that the roads are maintained in a certain condition and that a suitable dust is used.

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CHARACTER OF THE DUST

Finely-ground shale was used in the first experiments, and is still widely used. Experiments have been made with a variety of other materials, including sand, dolomite, Chance's mud, boiler ashes, gypsum, magnesia, sodium carbonate, soda crystals and Glauber salts. It is found that the minimum percentage that is necessary to prevent explosion varies widely, according to the substance used.

The following table shows for four different coal dusts the least percentage of quenching material that was necessary to prevent an explosion, in a specially designed apparatus.

TABLE XXV.

Coal used :	A.	B.	C.	D.
Boiler ashes	57	50	47	58-60
Quicklime	50	45	42-44	55
Ground shale	43	37	35	46
Chance's mud	38-40	30-33	29-30	39-40
Gypsum	33-35	26-28	26	35
Magnesia	28-30	28	25-26	32-33
Anhydrous sodium carbonate	12-13	10+	12	15
Soda crystals ($5H_2O$)	10	10-	9+	11
Soda bicarbonate	9-10	7	7	8-
Glauber salts ($6H_2O$)	8	8	7-	8-

Apparently, the quenching effect depends mainly upon the specific heat of the material.

At the same time, the efficiency with which a given material acts is greater, the more finely divided it is. This is shown in Table XXVI.

Thus, both Altofts shale and dolomite dust, when ground so that all passed a 28×28 sieve, and 55 and 66 per cent., respectively, passed a

200 \times 200 sieve, prevented the propagation of the flame from a cannon shot when they were mixed with the coal dust in the proportion of 1 : 1. Respectively 2 : 1 and 3 : 1 parts of these dusts were necessary when they were less finely divided.

TABLE XXVI.

Material.	Percentage by weight passing through :		Proportion of dust to coal required to prevent explosion.
	28 \times 28 sieve.	200 \times 200 sieve.	
Altofts shale . . .	65	18	2 : 1
Dolomite dust (fine)	68	42	3 : 1
Altofts shale (re-ground) . . .	98	55	1 : 1
Dolomite dust (super-fine) . . .	96	66	1 : 1

A light-coloured dust—for example, precipitated chalk or gypsum—possesses the additional advantage that it is readily visible, so that it is possible to tell almost at a glance whether the mine is in a safe condition; also, it greatly increases the illuminating effect of a miner's lamp, thus preventing many minor accidents along the passage ways.

EFFECT UPON HEALTH

Great care must be taken to ensure that the stone dust is without harmful action when inhaled by the workers. Haldane has shown that shale dust and powdered clay or chalk (free from flint or grit) may be used quite safely. On the other hand, there are two kinds of dust, the use of which may be injurious to health—namely, (a) dust from stones such as ganister or sandstone, which contain a large proportion of free crystalline silica,

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and are liable to break up into fine, sharp-edged particles, and (b) dusts of a gritty nature such as powdered slag, clinker or flue dust. The inhalation of the former may cause serious risk of phthisis, while the latter, though possibly not so injurious to the lungs *when mixed with coal dust*, may produce considerable irritation of eyes and throat, and predispose to bronchial ailments.

METHODS OF APPLICATION

The dust may be distributed throughout the mine by hand, being scattered from bags or trams, using a small shovel or scoop. The dust is thrown with sufficient force to dislodge accumulations of coal dust on timbers and ledges and in cavities, and to substitute stone dust. This is the most reliable and satisfactory method.

Attempts have been made to distribute the dust by throwing it into the ventilating current at the top or bottom of the down-cast shaft. It is found, however, that it is impossible to obtain an even distribution by this means. The heavy particles soon settle on the coal tubs and rails, and interfere with the traffic, while the finer portion, that is carried along the roadways for some distance, is only sufficient to deposit as a thin coating on the top of the coal dust. In some mines, the dust is distributed mechanically by compressed air.

DUST BARRIERS

In French mines, the stone dust is contained in boxes or on trays, that are supported above

the roadways. These "barriers" are adjusted so that they are readily tripped up by the pioneering wave and discharge a dense cloud of dust, which becomes mixed with the coal dust that has been raised by the pioneering wave, so that, when the flame arrives, the inert dust absorbs sufficient heat to quench it.

Dust barriers are effective in arresting the spread of an explosion, but they do not avert it, and a great deal of damage and loss of life may be caused before the explosion reaches such a barrier. They are only useful as additional safeguards, and as such they are used in this country. Explosions can only be prevented by stone-dusting every part of the mine, except the immediate face of each working place. An explosion of dust or gas at the face will die away at the mouth of the working place, if stone-dusting has been carried out efficiently.

Stone-dusting possesses a marked advantage over watering in that any failure to apply the dust for a day or two is not of such vital consequence as would be an omission to water the coal dust. The condition of the roadways can be determined by sampling and analysis, and recorded systematically. The method is not complicated, and the cost of installing the necessary apparatus is less than that of laying water-pipe lines throughout the passageways of a mine.

The majority of British mines have been using stone dust for the past four years. No coal dust explosion has occurred or has been propagated in any part of a mine that has been thoroughly

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stone-dusted. Only last year, an explosion of gas occurred in a Welsh colliery, but, owing to the adoption of efficient stone-dusting, the flame did not travel more than thirty yards before it was extinguished. Although over three hundred men were working in the mine at the time, six only were killed, and many of the others did not even know that an explosion had taken place. In the absence of stone-dusting, it is probable that the majority of the men would have been killed. There have been a number of disasters in mines in which the watering method was practised, or in certain parts of mines which were supposed to be naturally so wet that they did not need stone-dusting.

EXPLOSIONS IN COAL-GRINDING, -HANDLING AND -STORAGE PLANTS

Care should be taken to prevent dust explosions occurring in coal-handling and -storage plants, by removing the dust as it forms, and by keeping the plant as clean as possible. Where this is not practicable, every precaution should be taken to eliminate all possible sources of ignition.

Pulverised coal in bulk may be regarded as a coarse aerogel. It is not explosive, because its concentration is considerably beyond that of the upper explosive limit. It becomes dangerously explosive, however, when it is distributed in air to form an aerosol.

The risk of an explosive dust cloud being formed varies according to the design of the plant and the method of working that is employed. Generally

speaking, three distinct types of pulverised coal equipment are in use :

- (a) the circulation system ;
- (b) the indirect system ;
- (c) the unit system.

In the first system, the coal passes through a rotary drier to a dry-coal storage bin, or direct to the pulveriser, from which it is delivered into the pulverised-coal storage bin. The pulverised coal is delivered in regulated quantities to a fan, which forces it in a cloud through the main pipelines of from eight to sixteen inches diameter. Some of the coal is driven through branch lines to the furnaces as it is required, the remainder passing on through a return pipeline to the bin. Separate airlines carry to the burners the air necessary for proper combustion.

In the indirect system, the powdered fuel is transported mechanically, or by compressed air, to bins at the furnaces. From these bins, the fuel is delivered, by means of a small screw conveyor, either direct to the burner or to an air blast which projects it through the burner.

In the unit system, each furnace is provided with its own separate drying, pulverising and feeding installation.

An explosive dust cloud may be produced by dislodging or stirring up an accumulation of dust. All pulverisers, and conveying and elevating machinery should be dust-tight, so that dust does not escape into the surrounding air to settle on exposed surfaces. Absolute cleanliness should

be insisted upon in all buildings where pulverised coal is used. Accumulations of dust, wherever found, should be removed by suction—never by brooms or compressed air. Where, at present, it is impossible to prevent the accumulation of dust, it may be made safe by diluting it generously with four or five times its weight of pulverised shale.

Explosive dust clouds are being formed continuously in the pulveriser and in the conveying and elevating plant. It has been suggested that the coal should be pulverised, conveyed and stored in an inflammable gas—*e.g.*, methane—instead of in air, so that the coal dust could not take fire, while, at the same time, it would burn more effectively when it was projected into the furnace.

Many of the explosions that have occurred in pulverised fuel plants have been traced to the driers. These consist of rotating cylindrical steel shells, inclined to the horizontal, and are heated externally by furnace gases. The raw coal travels slowly through the shell.

In one case, a man in charge of a drier built up an abnormally large fire, so that the drier became overheated and the coal ignited. The flame passed to the pulveriser, ignited the fine coal dust, and caused an explosion that filled the whole building, killing two men and seriously burning two others.

A drier may be left stationary, with a small quantity of coal in it; this will become heated to the ignition point by the hot gases, and, on starting up the drier again, the glowing coal will be discharged into the pulveriser, to produce an

explosion, or into the dried coal storage bin, where it may start a fire.

When, for any reason, the fan is stopped, some of the dust settles in the pipelines, and, as soon as the fan is started again, it rises in a cloud. When the fan is stopped, smouldering particles of coal may enter the burners or the pipes leading from the burners to the main pipeline. When the cloud of dust is raised by the starting of the fan, such smouldering particles may ignite it.

It has been shown that the inflammability of coal dust depends very greatly upon the amount of volatile matter that the coal contains. It is probable that the use of the smokeless fuel that is obtained by the low-temperature distillation of coal would completely eliminate the danger of explosion in pulverised fuel plants.

When pulverised coal is stored in bulk—particularly, if it is in a warm place—it may oxidise rapidly enough to raise its temperature to the ignition point. It has been shown that if, at any point, the coal be heated up to from 150° to 170° F., heat will be developed by oxidation more rapidly than it is lost by radiation and conduction, so that the temperature gradually rises to the ignition point. It is necessary, therefore, to place storage bins containing pulverised coal as far away as possible from furnaces, open lights and flames, boilers and steam pipes, and flues.

Every precaution should be taken to ensure that all electrical wiring is adequately protected in conduits, and that switches be placed outside dusty buildings or be of some recognised safety

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design, and that motors be of the non-sparking type—preferably, squirrel-cage machines. All machinery should be well earthed to prevent sparks arising from the accumulation of static electricity.

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